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MULTIAPERTURE OPTICAL SYSTEM RESEARCH

Office of Naval Research
Contract Number
N00014-85-C-0862

FINAL REPORT

by

RTS LABORATORIES, INC.
1663 Technology Avenue
Alachua, FL 32615
(904)462-2666

November 6, 1987

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20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

A basic and applied research program concerned with multiaperture optics is described. The intent is to explore to what extent the principles of the insect eye can be incorporated into the design of optical instruments. The advantages and disadvantages of multiaperture optics are investigated in the basic part of the program. The applied part of the program was devoted to the design and construction of prototype instruments based on the design information generated during the basic part of the program.

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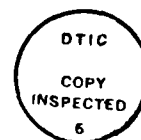**MULTIAPERTURE OPTICAL SYSTEM RESEARCH**

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PREFACE

The research program reported in here was a two year effort lasting from September 15, 1985 to September 15, 1987.

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I. INTRODUCTION

Multiaperture Optics Technology is based on the idea to use the design principles of the insect eye for optical devices having specialized applications.

It is the intent of the research program described in this report to explore the underlying basic optical principles in a basic part of the effort (see section II) and then go on and construct prototypes of actual devices utilizing these principles.

The point to be made was that for certain applications MAO principles are better suited than conventional optics. Therefore the prototypes were to be selected in a way that they could be compared to existing conventional devices.

The pupil tracker described in section V.A. can indeed be compared to other pupil trackers which are already on the market and is indeed considerablely smaller and less complex than these other systems.

There is an abundance of perimeters (described in section V.C.) already on the market but not one of them is suitable for fast screening. Only the MAO projector makes this possible.

The advantages of the surveillance lookout (described in section V.B.) is fairly obvious when compared to roving surveillance cameras.

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II. BASIC RESEARCH EFFORT

A. Multiaperture Optics (MAO) - Background

As pointed out above, the present research effort was devoted to build a device which incorporates at least some features of the insect eye (Multiaperture Optics). Obviously one needs to find out how the insect eye functions and then build an artificial device which operates on these principles. But the "bug" does not stop here, it starts here. The study of the insect eye is part of entomology. A person who wants to build such a device is undoubtedly a physicist or engineer. He is for the entomologist an outsider. On the other hand, the system wants you to test your theories by discussing them with the scientific community (experts), meaning one would have to go to the entomology conferences and publish in entomology journals, which means one has to become an entomologist first. Undoubtedly, that would not be very cost effective. Fortunately, there is a different way. The study of the insect eye may be a part of entomology but the laws of optics are a part of physics. There, as a physicist or an engineer, one may refrain from explaining how the insect eye functions, but one can take all the components in such an eye--the optical system, the detector system--and ask what kind of a device can one build using these (or similar) components and what can this device do for us. Never mind what it does for the insect, after all, our needs are different. Such an approach is indeed imitation of nature; it also clears a number of obstacles out of the way. Other than the formal ones mentioned above, the more immediate one, namely, is that it is not all completely understood how the insect

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eye works, however, we can find out what the components do once assembled.

1. The Insect Eye - As Seen by an Engineer

Based on the above comments, let's describe the insect eye in somewhat oversimplified terms, trying to concentrate on the components as they are, without guessing what they do for the insect, but what they will do for us. First, the overall systems. Some species have up to 20,000 eyelets. How do those function as a system? Logically there are three possibilities:

1. Each eyelet collects one pixel only and the resulting overall image is a mosaic (so called apposition eye).

2. Each lens of each eyelet projects a fairly large image onto the retina and all these images are superimposed precisely (so called superposition eye).

3. Each lens projects a small image onto the retina, the individual images do not overlap or overlap only to a minor degree.

Since each eyelet contains only 8 detectors, option 3 is not very likely to be used, however, for an artificial device it may be different.

Figure 1 shows the schematic diagram of one eyelet of an apposition eye, showing the basic components only but no anatomical details. The basic components are two lenses, a cornea, which is a regular lens, and a conical optical element. Right at the exit of the latter one, a hose-like structure containing the detectors is attached. A cross section through the detectors is shown on the side of Figure 1. There are seven to eight segments. The

detectors consisting of little tubes (microvilli) fill this hose-like structure. Light spirals down this hose guided by internal total reflection. The diameter of an individual eyelet is in the order of 100 micrometers. In the case of the apposition eye, each eyelet is optically separated--by pigment--from its neighbor.

Figure 2 shows one eyelet of the superposition eye. It is very similar to the apposition eye, only between the optical system and the detectors, a piece of fiber optics is inserted. At low light levels this piece of fiber optics is made to disappear optically, obviously by matching the refractive indices inside and outside of the fibers. At high light levels, pigment is moved between each eyelet and the superposition eye reverts to an apposition eye using the piece of fiber optics to couple the optical system to the detectors. The latter ones are separated as the little insert on the side of Figure 2 shows.

2. Multiaperture Optics - What is Different?

Are there new laws of optics, concerning multiaperture optics? Of course not, but the system is different. Therefore, the application of the known laws of optics to the multiaperture systems may result in something new or different. The first hunch is that there are phase relations between the many apertures. If they would play a major role it would be very difficult to build an artificial multiaperture eye. Fortunately nature has a similar problem, she may be very good in mass producing units, but the precision is poor. Nature is also very good in adaptation, meaning in this case, learning. The

Corneal Lens
Crystalline Cone
Pigment
Rhabdom
Retinula Cell
Nerve Fibre
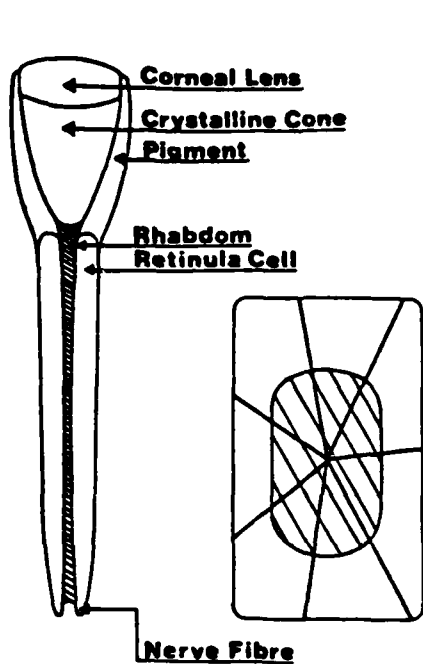
Figure 1.
The Apposition Eye

Corneal Lens
Crystalline Cone
Detectors
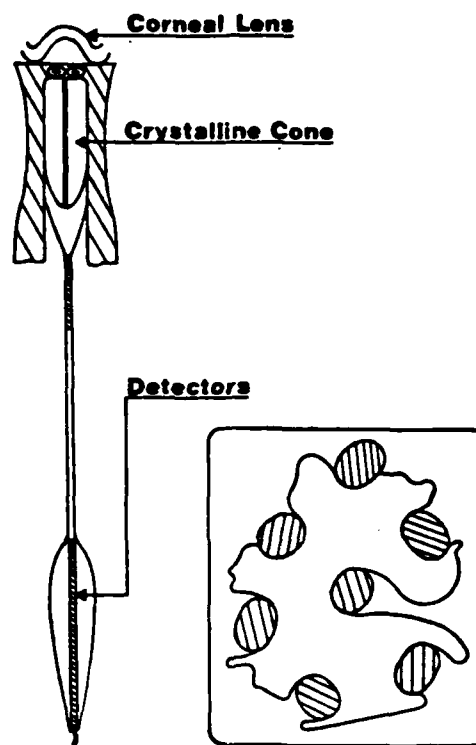
Figure 2.
The Superposition Eye

#1   #2   #3   #4
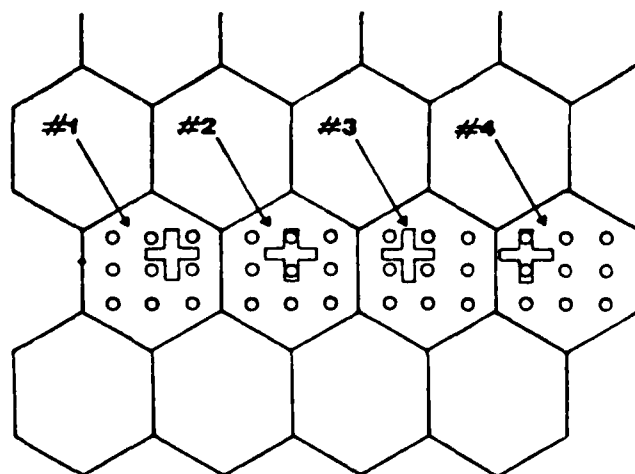
Figure 3.
Pseudo Scanning

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imperfect multiaperture eye--imperfect because each eyelet is different--is always distorting the objects in the same way. The distortions can be removed by learning. There is also endless duplication of what is seen, a typical design feature in nature. If one signal does not arrive, one of the many others duplicating this one will, in addition to many others, reassuring the brain the target seen is real.

Putting is more methodically there are at least three features unique to the multiaperture optics system. These are:

1. Pseudo scanning,

2. Pseudo dither,

3. Coincidence detection.

Let us assume each eyelet produces a small partially-overlapping image as indicated in Figure 3. The image is only probed by a few detectors, namely 8 in nature; for an artificial system it could be 9, 16, 25, or 36. In Figure 3, nine detectors are indicated, trying to probe the image of a plus--sign. In eyelet #1 none of the detectors report any intensity while in eyelet #2 detector 2 catches a part of the bar of the plus sign. In eyelet #3 the same spot falls between detectors again, while in eyelet #4 this spot is sensed by detector 1. What in effect happens is the same as if this spot were drawn across a detector by a scanning mirror. Thus, pseudo scanning requires no time--all detectors report, or at least "soak" simultaneously.

Depending in which direction the eyelets are pointed, pseudo dither can be accomplished the same way. Obviously it is easier to measure a change in intensity rather than its absolute value. Therefore dither is indeed very helpful, especially if noise is

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substantial. In such a situation, coincidence detection is also very helpful. This is also accomplished by learning. Obviously there are certain detectors in neighboring eyelets, which observe the same object point. In Figure 3 detector 2 in eyelet #3 and detector 1 in eyelet #4 are such detectors. Of course there are more in the eyelets above and below these particular ones. Therefore, if one detector sees a pulse at a particular time, the other must too. Once the system has learned which detectors are redundant, it can check for coincidences.

While the above mentioned features are certainly unique, the most unique one is the optical preprocessing which the many lenses must certainly do. This is simply due to the fact that small lenses have a reduced resolving power and therefore omit quite a lot of detail. This is beneficial since there is only so much information a brain can handle. The single lens eye removes detail by detector spacing, which happens after the details are optically acquired. In the fovea of a single lens eye the detectors are close together--so close to make the system diffraction limited. But this is only for a field of view of 1· degree radius. Outside the fovea the detectors are spaced further apart. These detectors will produce only crude outlines of an object, just good enough to cause attention and draw the gaze (field of view of the fovea) to the object of interest. In case of the multiaperture eye, there is, of course, no fovea inside the individual eyelets, and there is no eyeball which could roll to look at an object of interest.

However, it is conceivable that a group of eyelets could be designated to fill the function of a fovea. In this case, the

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focal length, and maybe the diameter of the individual eyelet and certainly the angle between the optical axes of these eyelets have to be different compared to the rest of the eye. This is indeed occurring and the term "fovea" is used for this region.

As can be seen there are quite a few options a designer can use to create a multiaperture optics device for a specialized purpose.

3. Multiaperture Devices - What can be Built?

Most animals equipped with multiaperture eyes are small. If we wanted to imitate nature, we will be well advised to keep the artificial multiaperture eye also small. But why would anybody want a small camera which has a poor resolution? The answer is maybe we do not want to take pictures with this camera which are intended to be viewed by a human observer. Instead, it could be a camera which recognizes objects and reports the presence of the object to the main computer of the vehicle or robot. If such a camera were the size of a postage stamp it could be fitted in the "hand" of a robot and make the task of picking up a certain object so much easier. Of course, the recognition scheme would have to be hardwired into the detector array; therefore, it cannot be too complex. Preprocessing by optical means as mentioned above is therefore beneficial.

For the artificial eye, we cannot possibly worry about focussing the many eyelets, and on top of it, adjust it so that individual images are superimposed correctly. Therefore, we do not want the superposition eye (option 2 above). For far distances we could use the fragmented image version (option 3)

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and operate it as a fixed focus camera, for close distances we could use the apposition eye (option 1). In this case, the total field of view of one eyelet creates only one pixel, therefore focusing--as a matter of fact image formation--is not necessary.

Let's discuss the latter one first. Here we need an optical system which does not necessarily have to form an image, meaning an object point is not necessarily represented as an image point; it could be a disk or a ring or something irregularly shaped as long as it fits on the detector. However, this optical element has to have a high light power and has to be easily manufacturable; since it has to be small, in the hundreds of micrometers in diameter. The light horn which is a conical hole with reflecting walls, fills these requirements nicely. During the present research effort, such an assembly containing in the order of a 1000 light horns was built. The entrance apertures are 300 micrometers while the exit apertures are 100 micrometers. The thickness of the masks is typically 2 mm. They can be bent over a sphere to any reasonable radius. The match between the (curved) output plane and the (plane) detector array can be accomplished by a fiber-optics faceplate.

Now we have an apposition image consisting of relatively few--in the order of 1000--pixels. Assuming we were right with the optical preprocessing, we should now have a recognizable digital image. What we need now are pattern recognition schemes specialized for low pixel numbers, which are simple enough to fit on a PROM to keep our multiaperture optics camera small.[1-3] Such schemes are being developed. They are based on the fact that the crude image will be a shadow-like outline of the object and that

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the machine has a-priori knowledge of the shape of the object it is looking for. It can be programmed that it only "sees" this very object, nothing else.

For distant viewing the fragmented image version (option 3) is a better solution, since the 1000 light horns will be too coarse a grid to discover targets at the horizon. Now one has to use lenses, and one is back to making images. A large number (hundreds) of 3 mm diameter and 6 mm focal lengths lenses seems to be a good solution. This is fairly large; the human iris can be as small as 2 mm diameter and we could cram a lot of detectors underneath it. If we did we would end up with an enormous image evaluation problem, requiring a large computer. No point of having a small eye then. If size is not an issue, a TV camera is certainly better than the multiaperture optics device. So we use fewer detectors, maybe 6 x 6 per lens and piece the image together by pseudo scanning. Now we have a system which is still slightly inferior in resolving power to the TV camera, but is still small and has a much larger field of view.

4. Applications

A multiaperture camera should be used for special applications only for which it is specifically designed. A hard-wired board, which can contain recognition codes, should be an integral part of the eye, it should be able to recognize objects and give steering commands to a vehicle or robot. A few of such special applications may be mentioned here.

a. Motion Detector

A MAO eye in the shape of a hemisphere can be mounted on the ceiling of a room to be safeguarded. The eye will be programmed to check for motion rather than recognition of shapes. This is probably the most simple application for MAO. The motion detector can be very powerful since it can work with coincidences. The algorithms for it are much simpler than the ones for recognition schemes.

b. Tracking and Measuring

Unpredictable phenomena like meteor traces or lighting paths can be followed by a hemispherical eye, similar to the motion detector mentioned above. Such an instrument could be used to do statistics on lightning or meteor showers. It could also be used for solar research although the sun travels slower. In this case, the size of an individual FOV will be chosen so that it will just be filled by the image of the sun. The rest of the eyelets will then be used to collect data concerning the scattered radiation, cloud coverage, etc.

c. Robotics

One problem encountered with robotics, which is new compared to conventional automation, is that the robot can move its arms freely and it can smash into objects or people. Therefore a visual system to prevent such mishaps would be very desirable. It is easily seen that a TV camera mounted on a central location (head) of the robot would require a large amount of computing power to recognize objects and correlate them in respect to the position of the arms. Obviously it is impractical to mount a TV

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camera on the moving arm. However, a postage stamp sized MAO eye can be easily mounted on the "hand". It will not be bothered by acceleration and deceleration. With a pair of these MAO eyes mounted, triangulation can be performed which would tell the system how far away the interfering object is. Obviously only the fact that an interfering object is present needs to be detected, not what it is. Therefore a simple recognition scheme which is of course handled in the eye itself, will suffice. Also since MAO is non-image forming, focussing of the eye is not required, which is very important for this particular application. A hand mounted eye could also be used to find and identify a certain part which the robot needs to install. Here of course a more sophisticated recognition scheme will be necessary. However, since a-priori knowledge exists, how the part looks like, the peculiarities of MAO can be used, so that the eye would only recognize the desired part while all other objects will be classified as interfering objects and will only become a concern if they are close enough to interfere with the movement of the arm.

d. **Parts Inspection**

As can be sensed by reviewing the applications discussed, so far MAO is best applied to situations where low resolving power and simple recognition schemes are adequate. A very good example is parts inspection. For example, if one wanted to inspect beverage bottles on the production line for cleanliness, absence of cracks, and absence of foreign mass, the recognition scheme seems to be so complicated (and therefore expensive to develop)

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that still, in many instances, a human inspector is used. MAO
however fills these requirements. Each individual FOV inspects a
certain volume element in the bottle. It is easy to define which
ones need to sense intensity and which ones need not. If there
is a foreign object in the bottle, only this fact has to be
detected, rather than the shape of the object itself. Therefore,
if one or more of the FOVs show a low intensity which should show
high intensity (empty) this is already sufficient to reject the
part. A smudge on the surface of the bottle can be detected with
intensity ratios between neighboring eyelets. The same is true
for cracks. It is also easy to adjust for different glass
coloration by simply averaging over the eyelets which view the
empty part of the bottle.

e. Gazing Sensors

Future military requirements will contain a greater
necessity to detect in which direction (e.g., in respect to his
helmet or in respect to the airframe) a pilot looks. For this
reason the movement of his eyes has to be monitored and the
center of the pupil has to be recognized. A MAO device is small
enough to be mounted in the rim of the helmet and observe the
pilot eyes without interfering with his vision and without adding
an undue amount of weight to the helmet. It is even possible to
mount the device in the lower (unused) part of the eyeglasses.
The recognition scheme is very simple and can be accomplished
inside the MAO device.

f. Blind Man's Eyes

A set of eyes which recognized objects and points out kind and position of such objects by verbal communications would be an invaluable aid for blind people. In principle this could be accomplished by two TV cameras served by a large computer. Obviously such a system would not be very practical. However MAO devices are small enough that they could be carried by a person. Recognition is done in the MAO eye already. What still needs to be added is a speech synthesizer which translates the output of the MAO device into words.

Only simple shapes would have to be recognized. For example, if an object is dead ahead, the shape of the object is not very important, but its distance is. This distance can be obtained by triangulation. Also moving objects are of importance. Any movement has to be considered as a threat and therefore detection of movement (motion detector) could be done without recognition of the moving object. Here recognition of simple shapes goes along with low resolution and makes this a practical device for a blind person to wear. Only a few words would be required for the speech synthesizer. They could be prestored in a chip and called when needed.

B. Non-Imaging MAO

Above it is shown that using pseudo scanning the image acquired can be detected and evaluated by fewer detectors, assuming there is an image. In this section the possibility to use non-imaging optical elements shall be discussed. The most likely element to use would be a light horn, which can be manufactured in small sizes, within reasonable effort.

The light horn is an interesting optical element which is a hollow cone with either reflecting walls or with a high refractive index fill providing internal total reflection. Nature uses the latter in addition to some modest gradient in the refractive index of the fill. For an artificial device both options are feasible.

The light horn was studied by Williamson[4] and Witte[5]. Welford and Winston[6] investigated it was a possible concentrator for solar energy. They came up with the "ideal concentrator", which has walls shaped like a rotation paraboloid, rather than a conical wall. An interesting side result of these studies was that the "ideal concentrator" supposedly has exactly the same parabolic shape as the conical optical element of the insect eye.

The desire to use the light horn as the major optical component in the MAO device provided the incentive to do a study on the optical properties of filled and unfilled light horns.

For light horns having an entrance aperture even as small as 100 micrometers, diffraction effects do not play a major role, and therefore it was decided to study the effects of geometrical optics on a fairly large light horn, mainly for ease of manufacturing the highly reflective walls. The experimental setup consisted of a Graphlex camera which was fitted with a board holding the light horn, rather than--as usual--the lens. The light horn entrance aperture is covered with a large photographic shutter. Several tests were made with this setup and are described in the following.

A parallel (incoherent) light source was mounted paraxially with the light horn in some distance (5 meters). The result of

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this test was a set of concentric rings as shown in Figure 4.

As will be shown below, these rings are not a diffraction pattern but can be explained with geometrical optics alone. Nevertheless, it is most astonishing that an empty cone should produce such a sharp image-like structure. In the next test a color filter was added to the white light source. The color filter consisted of two halves, a yellow and a red one, whereby the dividing line was located as a diameter of the light horn. The result is shown in Figure 5. The center disk is divided in a yellow and red half, the dividing line being the diameter of the center disk. The first ring is also divided into a yellow and red half along the same dividing line. However, amazingly the sides are reversed. While the left side of the center disk was red, in contrast to this, the right side of the first ring is red. For the second ring, the sides are reversed again, the left side of the ring is red.

Another test involved moving the light source off-axis by 5°. The result can be seen in Figure 6. The center disk is moved away from the center location, but otherwise intact. Superimposed on the center disk is a wedge (which may not be visible in reproductions of this paper) which is a mirror image of the weak wedge which occupies the center of the first ring. The latter one is now split into two, whereby the "twin" is on the left side of the first ring, while the second ring has also a twin which is on its right side. Also, remarkable is the sharp cutout in the first ring.

Moving the light source more off-center (11°) changes the situation even more drastically, as can be seen in Figure 7.

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FIGURE 4.
Parallel Beam - Parallel to Axis
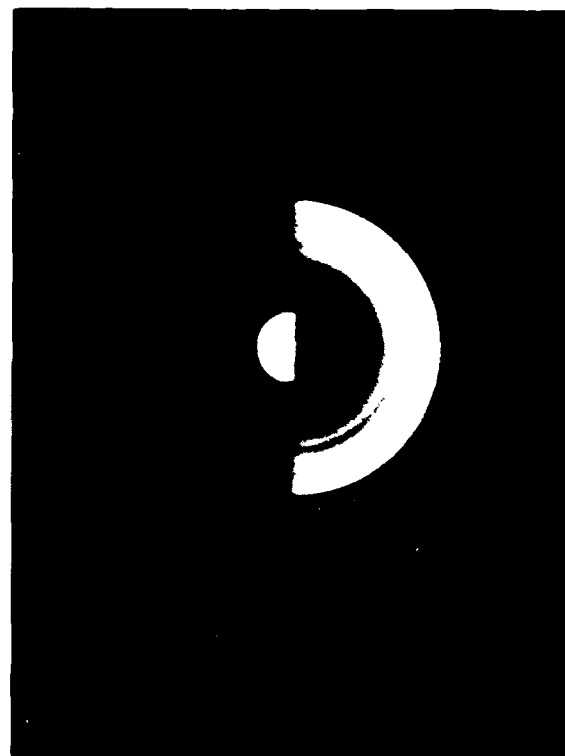
FIGURE 5.
Parallel Beam - Parallel to Axis
Yellow side right of Axis
Red side left of Axis

FIGURE 6.
Parallel Beam - 5° off Axis
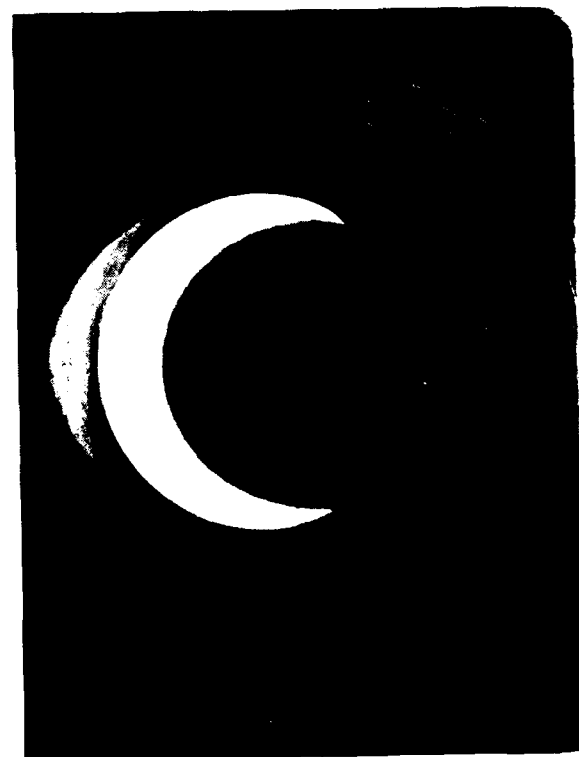
FIGURE 7.
Parallel Beam - 11° off Axis

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The center disk almost disappears. It can be made to disappear completely, using an angle of 12°. The first ring and its twin turn into crescents, while the second ring and its twin still seem to be intact.

While these results are certainly unexpected and interesting, one can also draw some practical conclusion from them. If one wanted to determine the axis of a parallel light source or the location of an object point at infinity with the light horn, one would put detectors in strategic locations to monitor the position of either the inner disk of the shape or positions of the rings.

Therefore, although the light horn is non-imaging, it is capable of more than just detecting the presence of an object point within its FOV namely it is also capable of determining, albeit crudely, where within its FOV the point is located.

1. Ray Tracing of Light Horn

The fact that there is a sharp edge on each ring as described above, as well as the fact that there is almost no intensity between the rings is most astonishing. In order to understand why this is the case, we present here a simple argument. Figure 8 shows an individual light horn and four mirror images. The real light horn is in the center, while the two on each side are mirror images. Assume a parallel light beam enters the light horn parallel to the optical axis (meaning an object point located at infinity on the axis of the light horn). The ray "1" would be the center ray of this beam, while the ray "4" would be the boundary of the beam. Only a part of the beam,

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namely the fraction between 2'--2 passes the light horn without interacting with the walls. This part forms the center disk as seen in Figure 4. The annulus 2-3 is reflected by the wall one time. The location and direction of the reflection can be found by letting the ray (e.g., "3") penetrate the wall into the mirror image of the light horn. This is indicated by the dashed line. Ray "3" happens to intersect the right edge of the exit aperture of the mirror image, therefore the real reflected ray will come out at the left edge of the exit aperture of the physical light horn, forming the ray "3R". Since there is a parallel beam assumed, all the rays must be parallel, and since the reflecting wall is straight (not curved), all reflected rays must be parallel to each other as well. This has some peculiar consequences. Considering the ray "2" one can see that any ray to the right side of ray "2" must be reflected, the one closest (infinitesimally away) to ray "2" turns into 2R, while the closes ray left of ray "2" goes straight through without reflection by the wall. The annulus 2-3 therefore forms the first ring. The second ring is analogously formed by the annulus 3-4.

Once the point is made and the formation of the rings is understood, it is easier to explore the influence of length and cone angle of the light horn by a ray tracing program.

The output pattern of the light horn was computed for the plane which contained the photographic plate. Figure 9 shows the output for a parallel light source. As can be seen, the obtained pattern agrees very nicely with the photograph (Figure 4). The next pattern, which is shown in Figure 10, corresponds to the photograph (Figure 6) and depicts the situation where the

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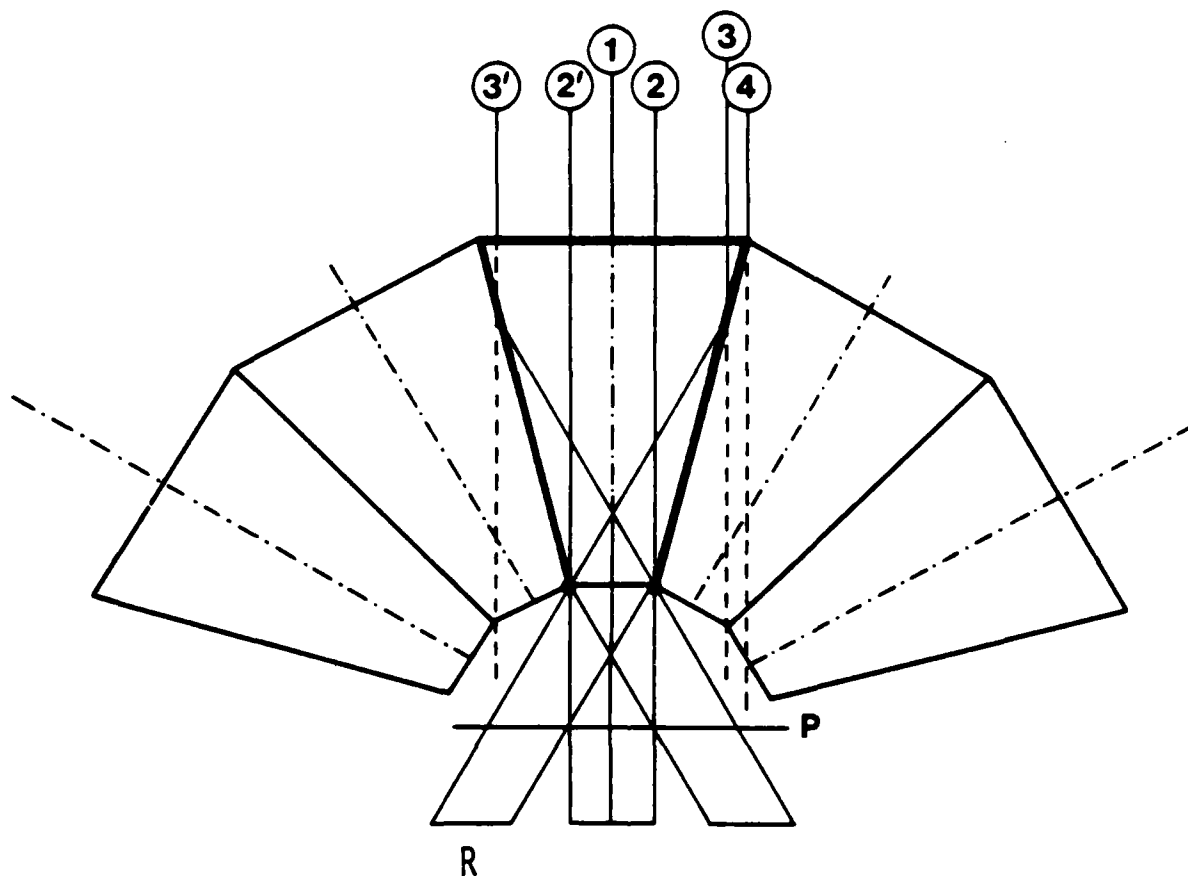
FIGURE 8. Ray Tracing for Light Horn Parallel Beam –
Parallel to Axis

3721 rays being traced.
Incoming ray angle: 0
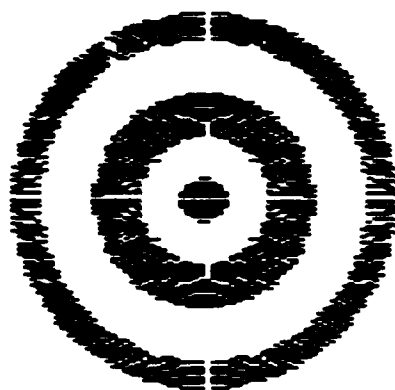
FIGURE 9. Parallel Light Source, Centered

Imcoming ray angle: 5
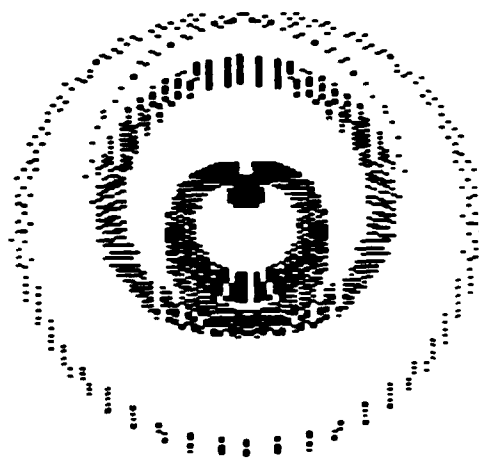
FIGURE 10. Parallel Light Source, 5° off Axis

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parallel light source is 5° off axis. Further output patterns
and description of the ray tracing program can be found in
Reference 7. From the discussions above one can see that the
light horn concentration light only up to the plane P in Figure
8. For parallel light, if a detector is placed anterior to this
plane, it will sense concentration (provided it intercepts all
the light outputted). If it is placed posterior to this plane,
all outputted light will be spread over a larger area than the
entrance aperture and therefore no concentration takes place.
However, in this case separation of light will take place into
several zones according to the off-axis location of the object
point.

2. MAO Camera

The basic concept of the MAO device is shown in Figure 11,
although at the present time some of the parts depicted are not
yet in place. As can be seen, the device will consist of the
following components: MAO mask, spacer, detector board, memory
board and hardwired processor board.

The MAO mask contains the light horns, possibly fitted with
field lenses. The detector board contains the detector array,
while memory board and hardwired processor board are used for
image processing and pattern recognition.

Only the MAO mask, spacer and detector board are in place at
the presently used MAO device. The functions of the memory board
and hardwired processor board are carried out by a computer
(P.C.). The detector board is an optical RAM manufactured by
Micron Technology, Inc. The designation is IS32A OPTIC-RAM. It

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nominally contains two arrays of 128 x 256 (each) silicon detectors although not all detectors are actually in place. Sensitivity is 2 J/sq. cm. at 900 nm. Each detector is 6.4 micrometers (center to center). The distance between two neighbors in a given row is 8.6 micrometers center to center. The somewhat unconventional arrangement of detector forces the user either to fill in the missing pixels by best guesses or omit certain detectors. At present we use only the detectors surrounded by a circle in Figure 12. This reduces the array to 64 x 128 detectors. Each detector element can be individually addressed although no use was made of this feature during the present effort.

Two different MAO-masks were used, one had cylindrical holes, the other had conical holes. The MAO mask which had a larger number of cylindrical holes was made of glass. The diameter of each hole is 100 micrometers. The distance between the holes is about 50 micrometers (150 micrometers from center to center). The mask is bent with a radius of 75 mm so that the angle between neighboring eyelets is 0.02 degrees. The mask has a diameter of 13 mm although only an area of about 2 x 5 mm (the size of the detector array) is used. A matrix of 12 x 30 holes is located over the detector array. Each hole should have a footprint containing 11 x 11 spaces for detectors which, however, are not all occupied. Figure 12 shows such an 11 x 11 field. The "footprint" of the round hole is drawn slightly larger in order to account for the small gap between exit aperture and detector plane. The detectors which are actually in place are marked with "x". The detectors actually used are indicated by a

24
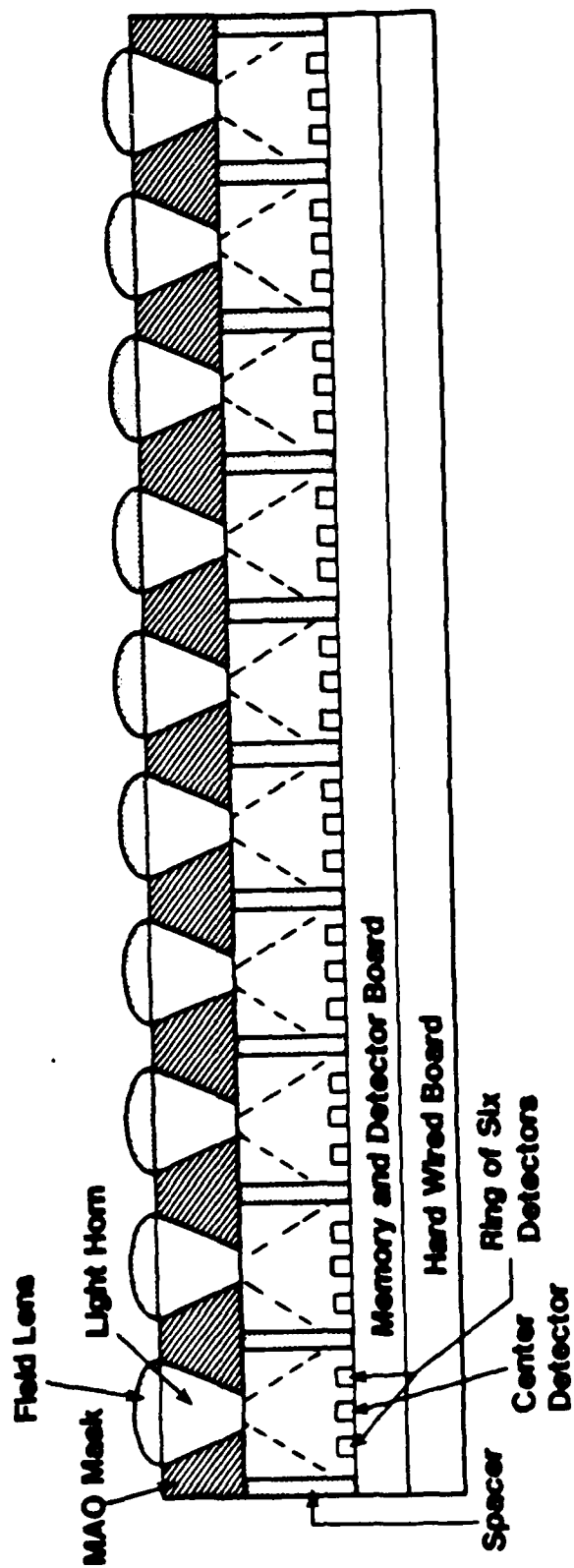
FIGURE 11. Multiaperture Optics (MAO) Device

Field Lens

Light Horn

MAO Mask

Memory and Detector Board

Hard Wired Board

Ring of Six
Detectors

Center
Detector

Spacer

25

128 DIRECTION

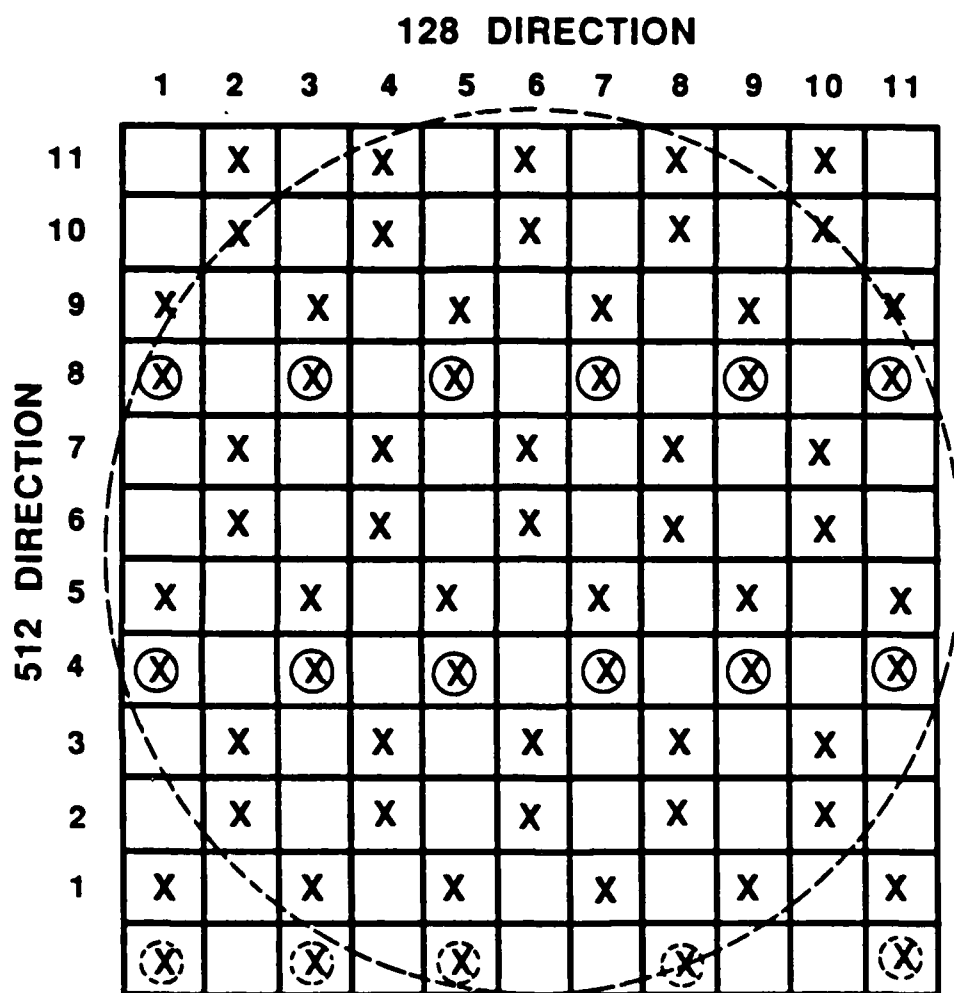|	1	2	3	4	5	6	7	8	9	10	11
11		X		X		X		X		X	
10		X		X		X		X		X	
9	X		X		X		X		X		X
8	⊗		⊗		⊗		⊗		⊗		⊗
7		X		X		X		X		X	
6		X		X		X		X		X	
5	X		X		X		X		X		X
4	⊗		⊗		⊗		⊗		⊗		⊗
3		X		X		X		X		X	
2		X		X		X		X		X	
1	X		X		X		X		X		X
	⊗		⊗		⊗			⊗			⊗

512 DIRECTION

FIGURE 12. Detectors Used

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circle around the x. Counting the actual detectors, one finds that there are 2 in the 512 direction and 6 in the 128 direction.

Figure 13 shows the image of an "N" and an "H", taken by the camera with a mask having cylindrical holes.

It is, of course, preferable to have conical holes (light horns) instead of cylinders. Also, the walls of the cones should be coated with a highly reflecting layer. In addition, the cones should be closer together than one diameter of the entrance aperture. These requirements are met by a second MAO mask which was also used. The holes were indeed conical, had an entrance aperture of 300 micrometers and an exit aperture of 100 micrometers. This distance between two entrance holes (center to center) is 325 micrometers. Figure 14 shows the same target as in Figure 13 but taken with the camera having conical holes (light horns).

The fact that the slanted part of the "N" and the cross bar of the "H" is fatter than it should be, is a result of the particular arrangement of the detectors. This fact was discussed in more detail in the Reference 3. Since this is a consistent phenomenon, the image could be cleaned up by suitable software.

Figure 14 shows a poorer definition, especially at the "N" than Figure 13 shows. However, one has to consider that the entrance aperture is now 300 micrometers and that the angle between eyelets is now twice as much as the mask of Figure 13 had. The difference between Figure 13 and Figure 14 is really a demonstration that the resolving power of the apposition eye depends on the FOV of the individual eyelet.

In addition to the distortion caused by the detector

arrangement the printer also introduces some distortion. It is, therefore, more advantageous to view the binary image rather than the analog output of the printer. Figure 15 shows the binary image of Figure 13, while Figure 16 shows the binary image of Figure 14. Each detector which receives intensity larger than a preset threshold level generates a binary one while all others generate a binary zero. The letters come out clearer in this representation. In order to improve the quality of the images it would be necessary to read all detectors, not only the ones circled in Figure 12. Also the additional resolution to which the light horn is capable owing to the phenomena discussed above should be utilized.

As can be seen in Figure 1, the light horn in the insect eye is connected to a cylinder which contains the light detectors; called microvilli (see Figure 17), which may divide the cylinder in a multitude of pixels; albeit in direction of the cylinder axis rather than perpendicular to it as one would expect for a focal plane array. Since one of the authors of this report (RTS) applied several years ago for patent[8] describing a similar detector (see Figure 18) it seemed to be a good idea to investigate this configuration more closely. Therefore an experimental set-up, as shown in Figure 19, was used to explore if in addition to the rings found in horizontal cross section of a pipe attached to the cone, also significant information could be gathered by examining the surface of this pipe in the direction of the optical axis.

Therefore ray tracing programs were written which calculated the patterns produced in the posterior cylinder by reflections occurring in the anterior light horn (cone) or by rays which pass

FIGURE 13. Mask with Cylindrical Holes

FIGURE 14. Mask with Conical Holes

BIT MAP LISTING FOR FILE C:CHART1G1.DAT

FIGURE 15. Binary Image of Figure 13

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BIT MAP LISTING FOR FILE C:RTSCHAR4.DAT

FIGURE 16. Binary Image of Figure 14

Microvilli

←—Retinula cell

FIGURE 17.   Microvilli

Signal Wire

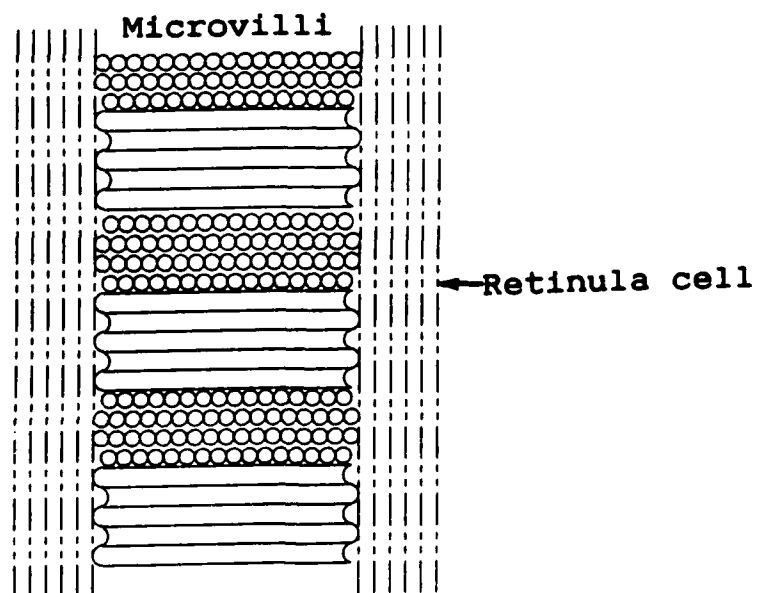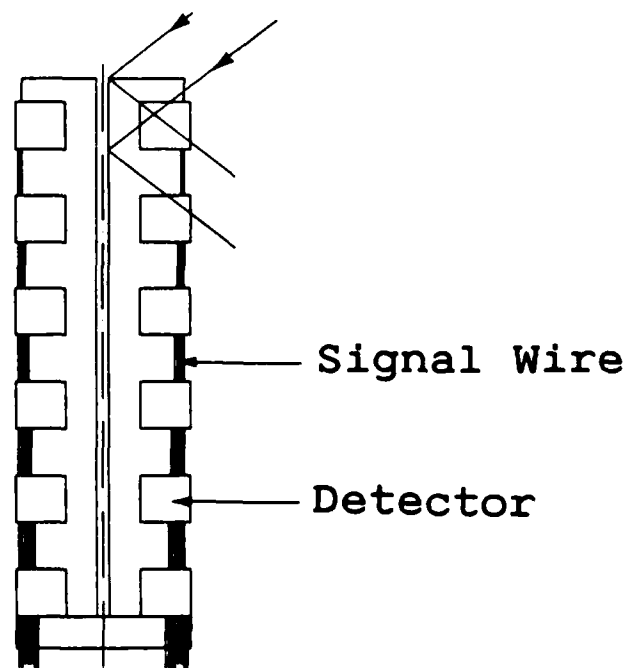Detector

FIGURE 18.   Fiber Shaped Detector.

through the light horn without reflection. The results reported here are only for object points at infinity. A mirrored wall on the light horn was assumed. The computer programs calculated patterns (1) at vertical cross sections of the cylinder (at various distances from the light horn), (2) on the wall of the cylinder, (3) at horizontal slices through the cylinder (at various elevations). In general, only the unreflected light rays and singly-reflected rays were important; and doubly-reflected rays appeared only at larger polar angles where poor resolution destroyed their usefulness. (Note: all dimensions below are in arbitrary units of length, with one unit representing the entrance aperture radius of the light horn. For the same relative dimensions, the results will all scale linearly.)

Figure 20 shows typical patterns at three different vertical cross sections down the cylinder when the object point is on axis. The light horn chosen in this section has an entrance aperture radius of 1.0 unit, an exit aperture radius of 0.8 unit, and is 19.0 units long. (The radius of the cylinder is 1.0 unit.) The image is approximately in focus in 20(a), which is 33 units down the axis (e.g.,20(b) at 48 units) until the reflected rays begin to impinge on the cylinder wall in 20(c), at 86 units. Unreflected rays pass directly down the cylinder and can be recognized by their rectangular array characteristic.

Figure 21 shows the pattern of rays impinging on the wall. Here the abscissa represents distance down the cylinder while the ordinate represents angle around the axis. (One may imagine that the cylinder has been cut along the top and then unrolled and flattened.) The on-axis object point has produced a uniform band

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around the cylinder wall at a distance from the light horn of 70 to 80 units. Unreflected rays provide a weak and nearly uniform background on the cylinder wall (which is not shown on this plot).

Figure 22 shows a typical vertical cross section pattern for an object point one degree off axis, at 70 units down the cylinder. The rays eventually form a nearly circular cross section and impinge on the cylinder wall closer to the light horn than did the on-axis source rays. Figure 23 shows the wall pattern. A somewhat distorted band is produced between 34 and 47 units down the cylinder, and the unreflected rays form a more intense background, producing the horizontal elliptical pattern at the center. Figure 24 is the wall pattern for an object point two degrees off the optical axis.

The width of the bands produced on the cylinder wall is a measure of the polar angular resolution of the device, while the distance of a certain observed band from the on-axis "zero" band (the band caused by an on-axis object point as shown in Figure 21) is a measure of the polar angle of a certain object point. Figure 25 plots the distance of the center of various bands from the "zero" band as a function of off-axis polar angle for several different light cones. The center point (B_c) and the width (B_w) of the "zero" band can be found by the following equations (symbols as in Figure 19):

$$B_c = [(D_c + A_\bullet/2 + A_i) \cot(2\alpha + \gamma_i) - L]/2 \qquad (1)$$

$$B_w = [L - (A_i - A_\bullet) \cot(2\alpha + \gamma_i)/2]/2 \qquad (2)$$

34
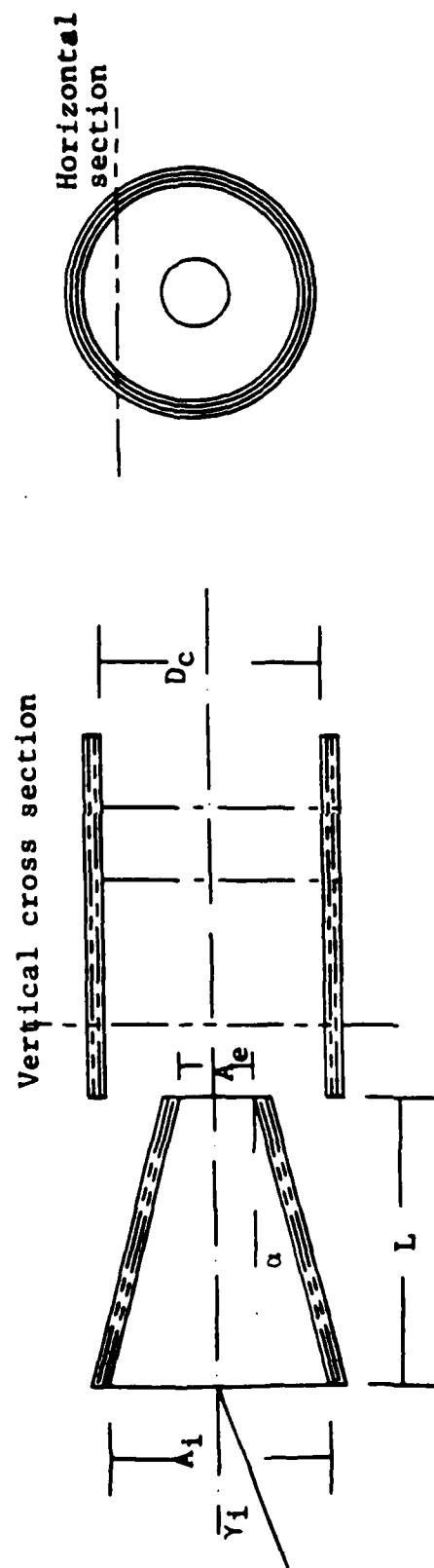
FIGURE 19. Schematic of Device

(a)   (b)   (c)
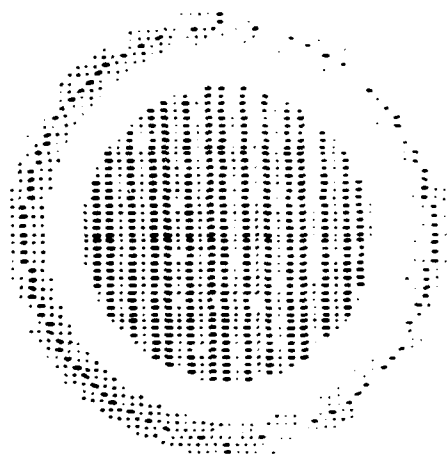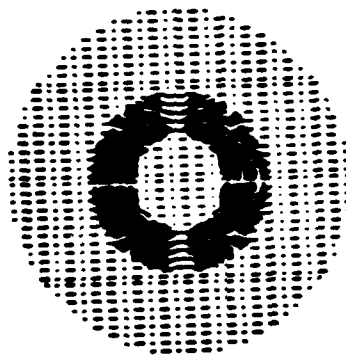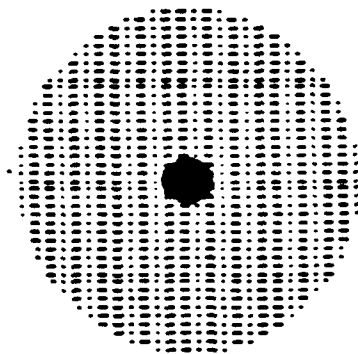
FIGURE 20. Vertical Sections Across Cylinder

36
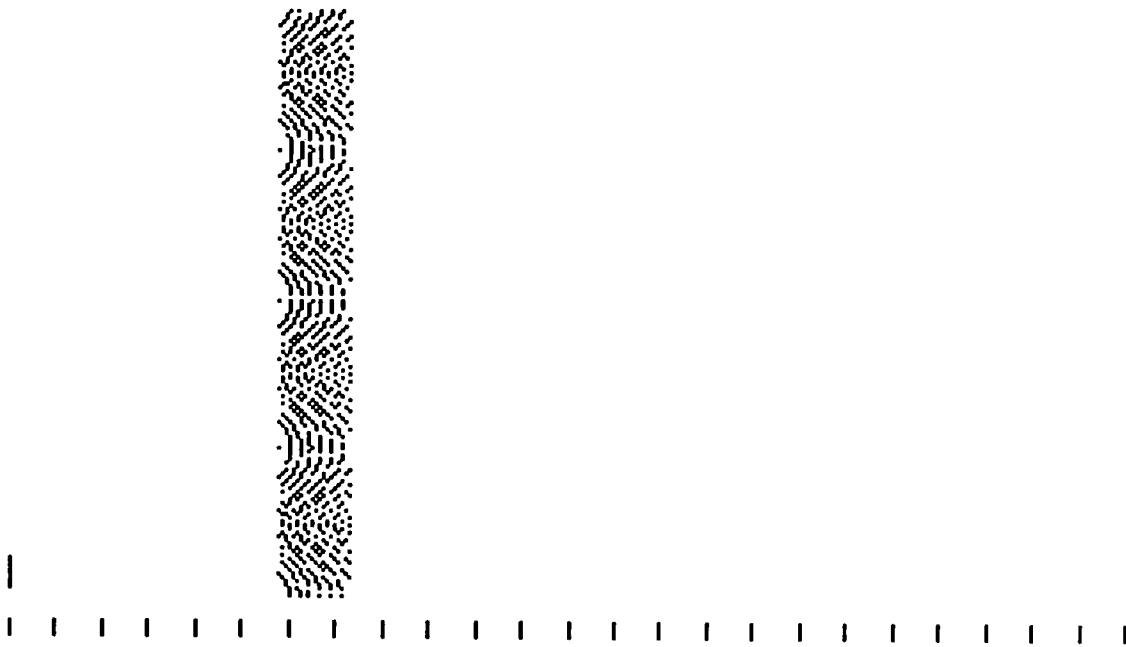
FIGURE 21. Ray Pattern on Cylinder Wall
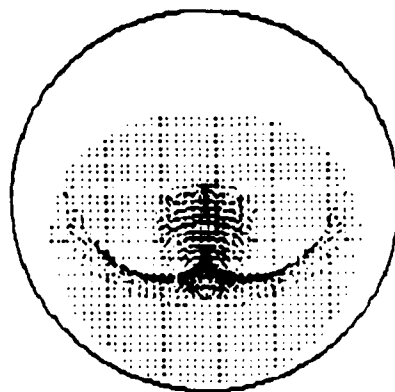
FIGURE 22. Object Point One Degree off Axis
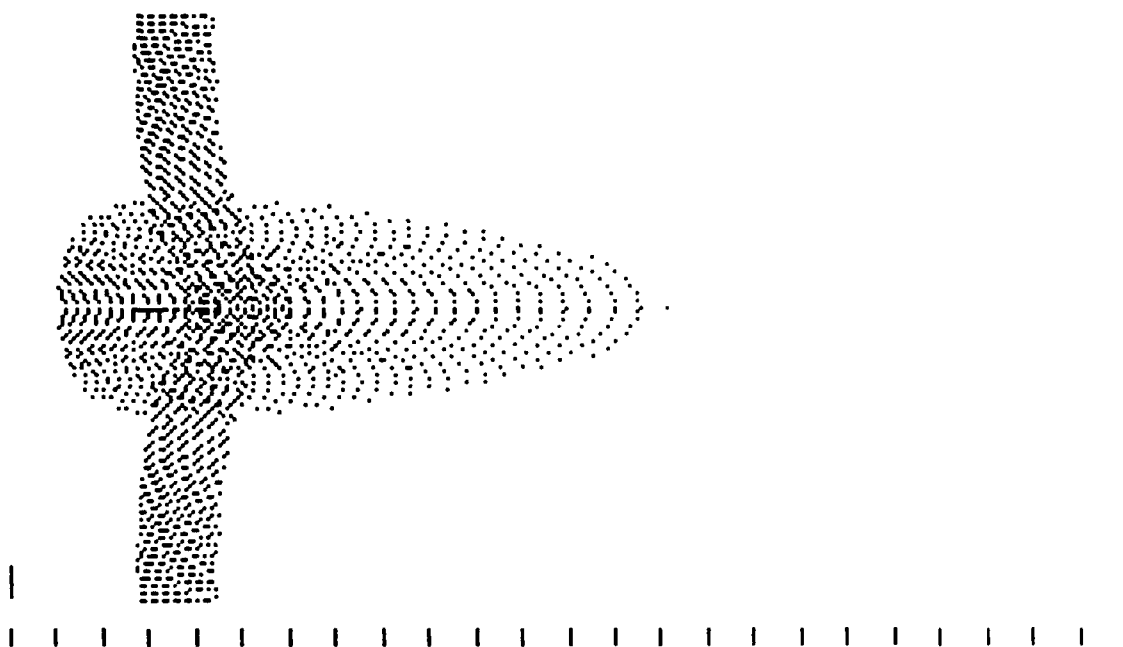
FIGURE 23. Ray Pattern Impinging on Cylinder Wall For
Object One Degrees off Axis
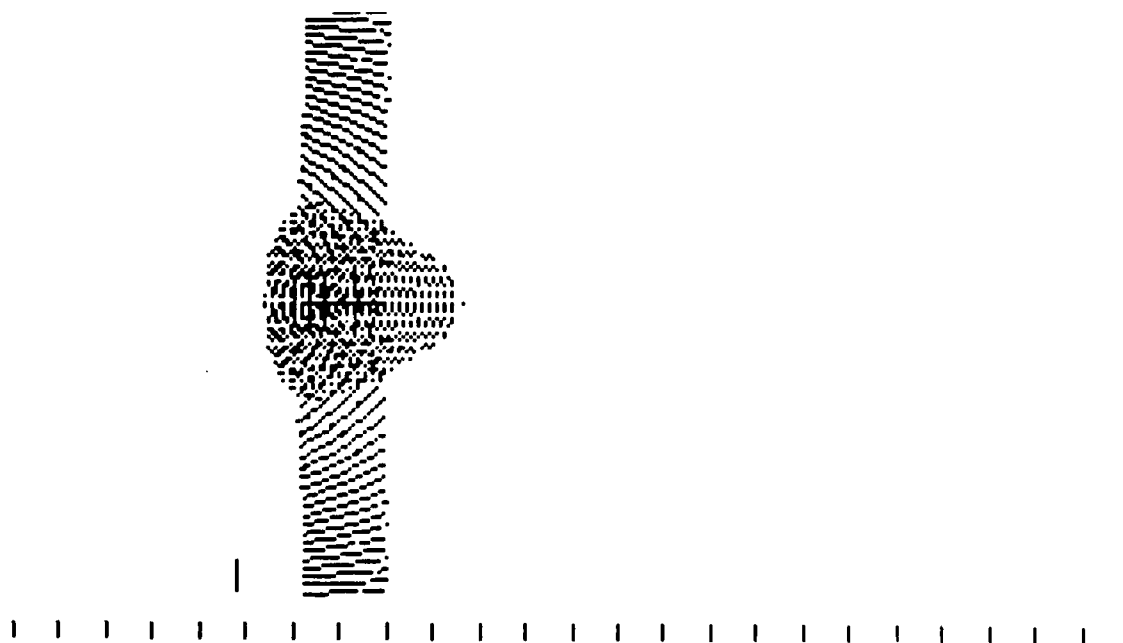
FIGURE 24. Ray Pattern Impinging on Cylinder Wall For
Object Two Degrees off Axis

38
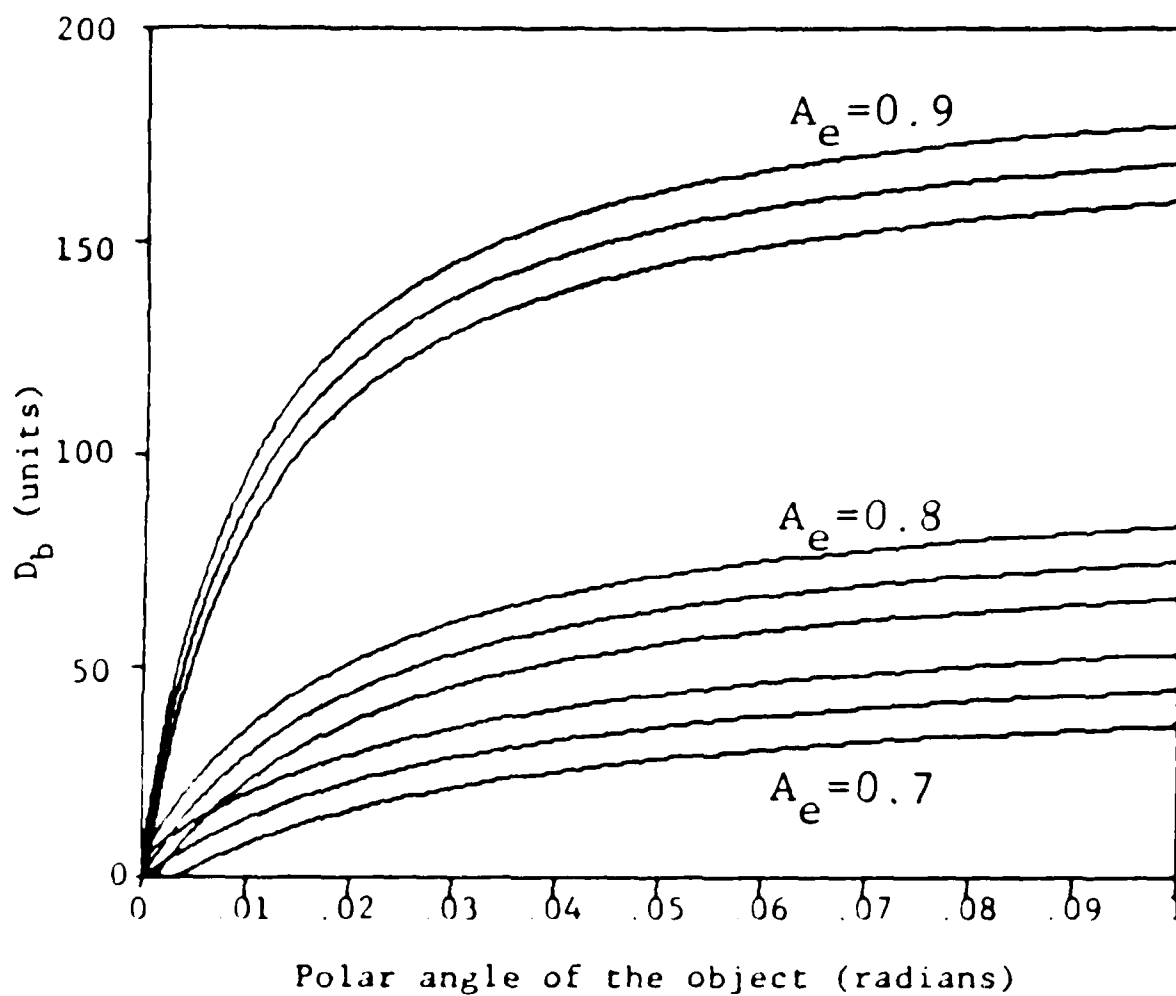
FIGURE 25. Distance of Center of Bands From "Zero" Band vs. the off-Axis Angle

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and the equation for the distance (D_b) between the zero
band and an off-axis angle band (one reflection only) would be

$$D_b = (D_c + A_i/2 + A_\bullet/2) \, (\cot(2\alpha) - \cot(2\alpha + \gamma_i)/2. \qquad (3)$$

In each case, the radius of the entrance aperture of the light
horn is 1.0 unit. The horns are 19 units long and have exit
aperture radii ranging from 0.7 unit to 0.9 unit.

If two object points are present at different polar angles,
they may be distinguished if their respective bands do not
overlap. The band width, B_w, may be thus converted to
polar angles and the angular resolution plotted as a function of
polar angle as in Figure 26. The value plotted is the full-width
of the bands converted to polar angle in radians. The angular
resolution improves as the light horn exit aperture approaches
the size of the entrance aperture. The fraction (F) of the total
light incident on the horn which is reflected to form bands is:

$$F = (R_0^2 - R_1^2) \, / \, R_0^2 \qquad (4)$$

where R_0 is the entrance aperture radius, and R_1 is the exit
aperture radius. Hence, the resolution improves at the expense
of the efficiency as one might expect.

The unreflected light patterns (for example, the central
elliptical patterns in Figures 23 and 24) could conceivably be
used to distinguish objects at different azimuthal angles.
However, for the geometries studied here the azimuthal angular

40
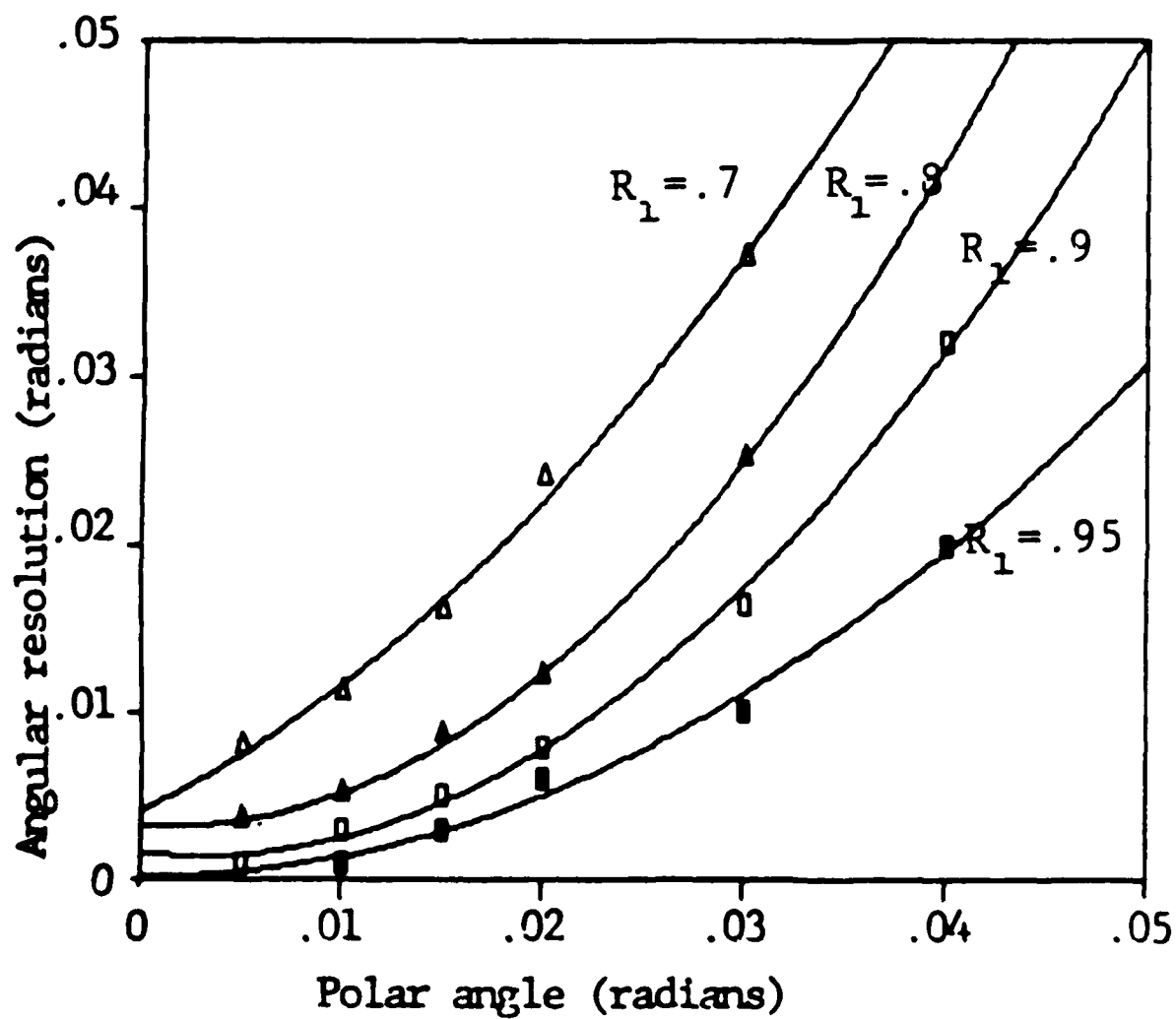
FIGURE 26. Angular Resolution

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resolution would be very poor. More precise azimuthal angular information can be obtained by cross correlation between several eyelets as discussed in Section 4 below.

As far as the polar angular resolution is concerned it is of interest to see how it varies with the length of the light horn when the entrance and exit apertures are kept constant (light concentration ratio being thus constant). Figure 27 shows the results for an entrance aperture radius of 1.0 unit, an exit aperture radius of 0.8 unit, a cylinder radius of 0.8 unit, and various horn lengths from 5.0 to 60.0 units. The comparison is made for an object point one degree off axis. Optimum resolution appears at a length of about 20.0 units.

The polar angular resolution of the device is thus limited by (1) the width of the bands, (2) the presence of background from the unreflected rays, and (3) the distortion of the bands for off-axis object points. Nevertheless, a number of angular bands may be distinguished. For example, one of the devices studied numerically and fashioned experimentally had parameters:

```
Entrance aperture radius......1.0 unit
Exit aperture radius..........0.8 unit
Cylinder diameter.............1.0 unit
Light horn length.............19.0 units
```

The data indicates that this device might be fitted with sensor rings inside the cylinder as shown in Table 1:

Table 1. The Distance-Polar Angle Relation of Light Horn Used

Distance from light horn (units of entrance radius)		Polar angle range (milliradians)		
80. to 72.	.....	0.0	to	1.5
72. to 61.	.....	1.5	to	4.5
61. to 49.	.....	4.5	to	8.0
49. to 42.	.....	8.0	to	13.5
42. to 29.	.....	13.5	to	24.0
29. to 15.	.....	24.0	to	50.0
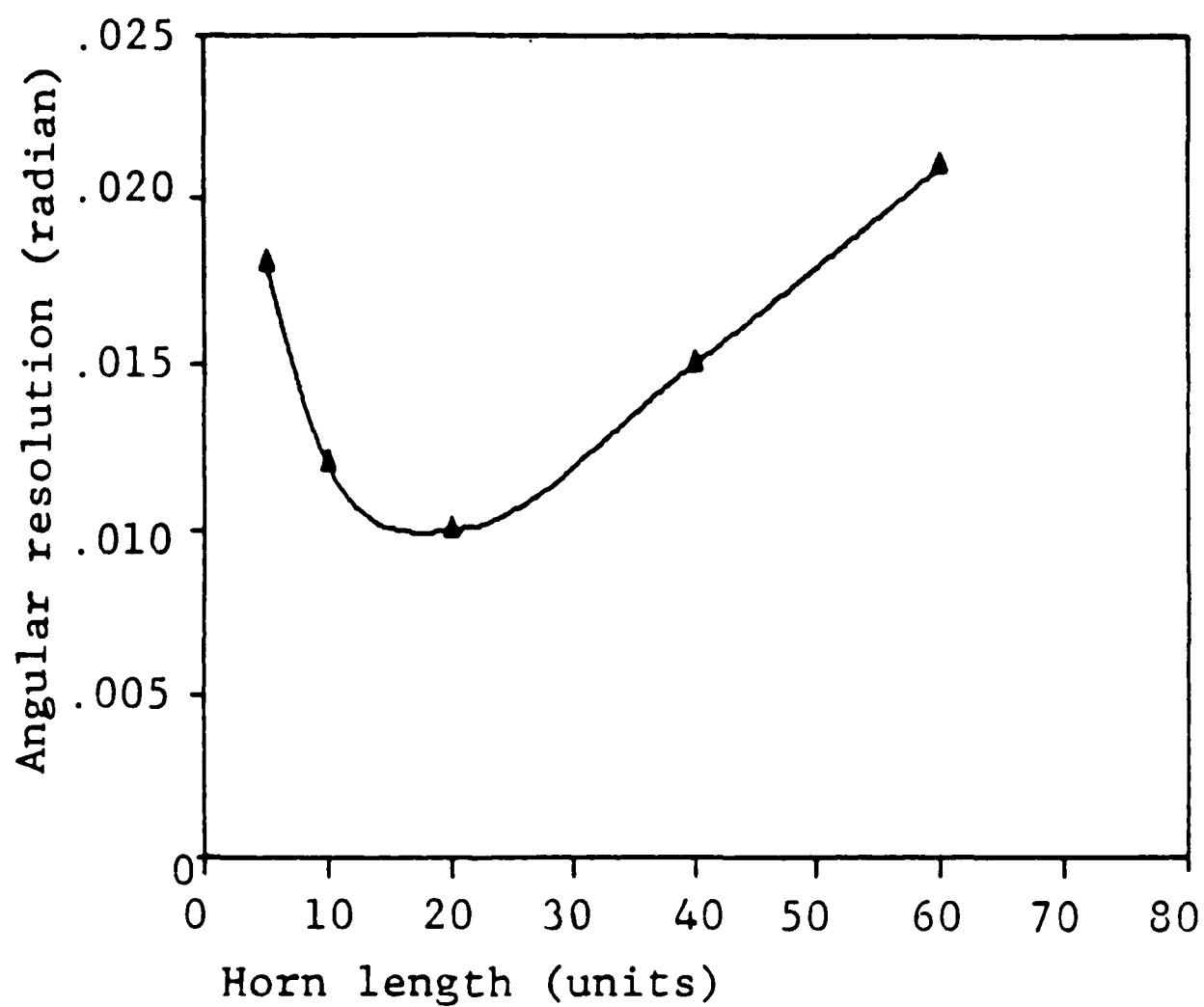
FIGURE 27. Angular Resolution Versus Light Horn Length

If this horn-cylinder combination were used as a simple collimator, it's light acceptance would be characterized by the half-angle of the 1 x 19 unit collimator, i.e. about 0.05 radian. Thus use of the reflection bands on the cylinder wall enables finer resolution and possible imaging within a single collimator tube. If the light horn with an exit aperture of 0.95 unit were used, about 20 distinguishable angular ranges would be obtained. However, the reflecting surface area would drop from 36 percent of the total entrance aperture to about 10 percent and the length of the cylinder would need to be increased from about 150 units to over 300 units.

It is interesting to find out how the patterns observed on the cylinder wall would look on a horizontal section through the cylinder at an arbitrary elevation. Such a pattern was computed for the plane located 1.0 unit above the optical axis and is shown in Figure 28 (the object point was on axis).

In order to obtain experimental verification of the above calculation a light horn-cylinder combination was constructed. Table 2 shows the dimensions of the experimental device.

Table 2.   Experimental Device

Entrance Aperture Radius:	9.18 mm
Exit Aperture Radius:	7.35 mm
Light Horn Length:	174.50 mm
Cylinder Radius:	9.50 mm
Cylinder length	1219.20 mm

A helium-neon laser beam was used to simulate an object point at infinity. The beam was expanded to a diameter larger than the entrance aperture of the light horn. Figure 29 shows a

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photograph of the pattern as it appears at a vertical cross section of the cylinder, this figure corresponds to the Figure 6(a), showing the calculated pattern. Note that focussing takes place, while no compound curved surfaces are involved in the optical system. The fine structure seen is caused by the laser and should be considered as an artifact.

Figure 30 shows a photograph of the light patterns observed down the cylinder. A frosted glass tube was attached to the exit aperture of the light horn and the resulting luminous wall pattern was photographed. (The center of the pattern is on the bottom of the tube and the photograph was taken from the side.) The gap in the band is caused by the laser. Finally, Figure 31 corresponds to the calculation shown in Figure 28. Of course, the photographs show more detail than the ray tracings predict, which is to be expected since multiple reflections and diffraction effects were ignored.

From the reflection pattern numerically and experimentally observed thus far, it seems unlikely that a single horn-cylinder combination can do more than determine the polar angle of objects in its field of view. At any polar angle, the patterns are quite insensitive to azimuthal angle. The production of an image of the distant object-space will then require at least three adjacent "eyelets" with overlapping fields of view. The patterns detected at the various longitudinal positions along the wall of the cylinders must then be correlated (by addition, multiplication or other operation on the three signals). The two dimensional area imaged is indicated by cross hatching in Figure 32.

Imcoming ray angle: 0
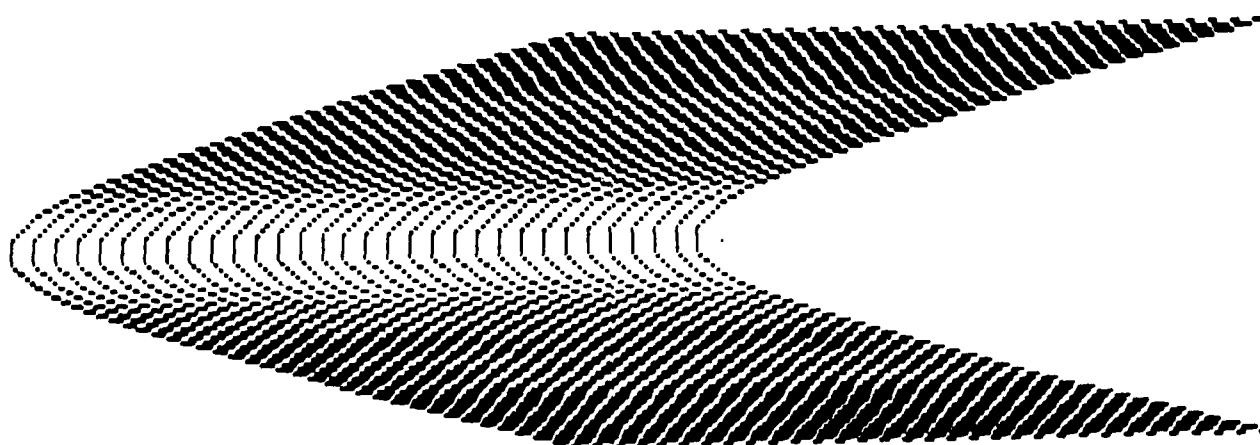
FIGURE 28.   The Pattern Which Would Appear on Horizontal
Slice

FIGURE 29. Cross Section Photograph Pattern
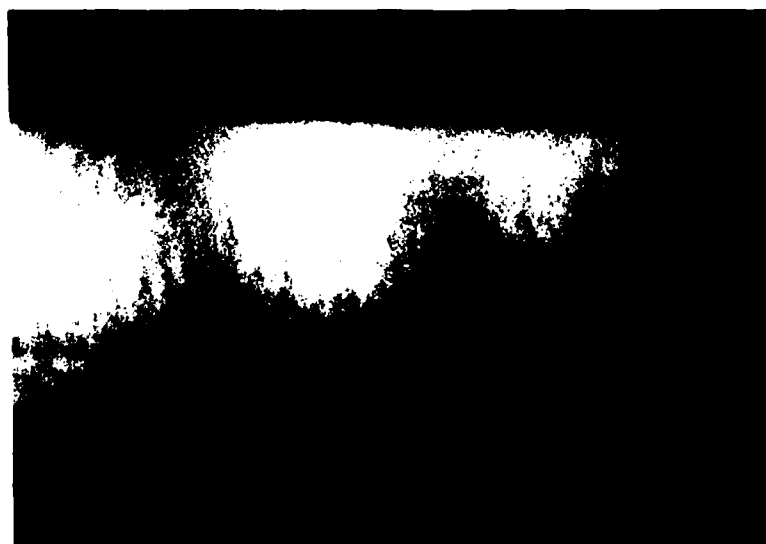
FIGURE 30. Pattern on Cylinder Wall

FIGURE 31. Pattern on horizontal slice

Object area seen by
all three eyelets
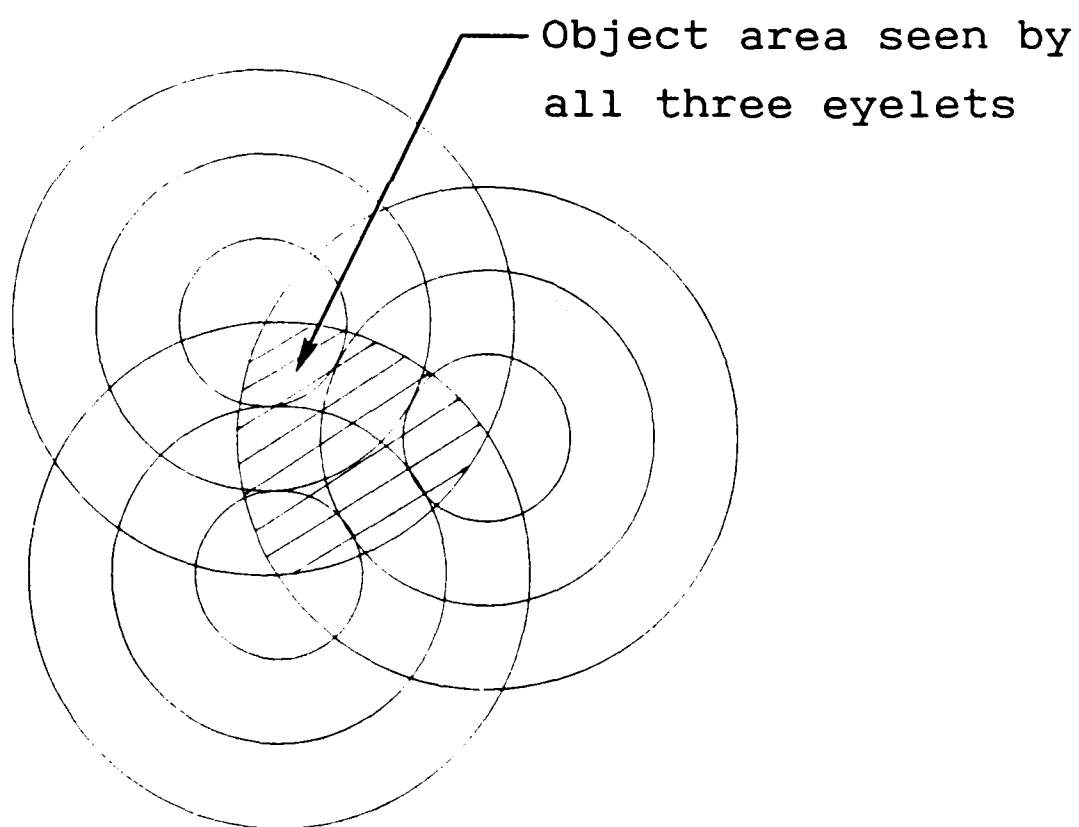
FIGURE 32. The Correlation of the Image Information
Among Three Adjacent Eyelets

A study has been made of the imaging possibilities of a long cylinder lined with light sensors and equipped with an input light horn. The patterns of (a) unreflected rays, and (b) singly reflected rays have been observed to encode a distant object-space in a fairly simple fashion within the receiving cylinder.

In conclusion one can say that a single eyelet can distinguish objects at different polar angles, but not at different azimuthal angles (when reflected rays are used). The maximum polar angle from which useful information may be obtained is about the half-angle of acceptance of the truncated light horn (when used as a collimator for instance). The angular resolution may be optimized by proper selection of the light horn length, and the angular resolution may be improved (at the expense of efficiency loss) by reducing the half-angle of the conical light horn.

C. Imaging MAO

The main feature of the above described non-imaging MAO were low resolution (which can be improved by the techniques described) and therefore as a consequence one avoids overwhelming the image evaluation system albeit at the expense of detail.

If one wants to use imaging MAO, meaning use of lenses instead of light horns, one is faced again with the number one problem of image evaluation, namely collecting too much information; however still retains the other advantages of MAO namely small size of the device and large field of view.

Therefore it is opportune to divide Imaging MAO into

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recognizers and non-recognizers. The non-recognizer is a device which although offered a great mass of data will accept or read only a small fraction of the detectors, maybe every tenth. Then it will wait for a certain time and acquire the same information again and subtract the obtained image from the previous one. The result of the computation is, assuming nothing has changed in the scenery, just some noise. However if an object has moved, it's image will show up as a result of this computation. If the movement was sufficient actually two images will appear, namely a positive and a negative. One of the images will indicate where the object was, the other one will indicate where it is now. Since only every tenth detector was read, it could be that actually two unrecognizable images are obtained, namely two areas of apparently increased noise activity. Therefore once such noise "islands" are obtained it is time to read all detectors around these islands. Now one should obtain both images, the positive and the negative one. If the scene in which the object moves is rich in detail, the scenery covered and uncovered by the object will appear superimposed negative and positive respectively. But since the device is a non-recognizer, meaning it is only interested in the presence of a target, but not in identifying it, this is not a serious problem. Basically this is the most efficient way to establish the presence of a moving target.

There are numerous applications for a device like this. It should be born in mind that the device is small and can be built having any desired field of view. For example, it could be used as a security device hanging on the ceiling of a room to be

checked for intruders. It could be an anti-collision device for

small airplanes, assuming the other airplane is equipped with a

strobe light, or it could be a ship's lookout checking for

attacking airplanes or missiles.

During the present effort such a device was designed and

constructed. It is described in Section V (Surveillance

Lookout).

If one is interested in imaging MAO of the recognizer type,

one has to deal with the data management problem caused by the

large mass of information contained in a scenery.

One possible way to deal with this is through the concept of

the fovea. The human eye uses this principle. In the fovea the

detectors (rods and cones) are so close together, as the

diffraction limitation of the optical system allows. In the rest

of the retina, the detectors are far apart creating an image only

good enough to check for movement. If movement is detected the

eyeball is rotated until the moving object is acquired by the

fovea.

For an artificial device the concept of a fovea can also be

used, however movement of an eyeball, in this case the MAO device

would not be very practical. Therefore one has to move the fovea

itself. This is realized in a concept developed under the

present effort intended to be used in a pop-up periscope. This

concept is described in more detail in Section III (Pop-up

Periscope). The idea is to use the MAO device to "scan" the

horizon simultaneously for a target, while rotating a mirror

serving a stationary fovea. Once a target is found the mirror

rotation is stopped at this position and the fovea is exposed to

the target only. Obviously target detection and acquisition can be done considerably faster than the deployment and retraction of the periscope can be accomplished.

A different way to move the fovea can be accomplished electronically. Let's assume detector arrays are inexpensive enough that it is feasible to cover the whole image area with high resolution, however the image evaluation system is not capable of digesting (in a reasonable time) the mass of data which would be obtained if all detectors were read. Therefore the solution is to read only a small fraction of the detectors with the exception of a fovea sized field where all the detectors are read. This field can be scanned electronically across the total image field until a target of interest is discovered. From then on the fovea can stay with the target, wherever it moves.

The scanning of the fovea across the image field is accomplished by reading all detectors each time at a different location on the array. Of course the typical image content is so large that a multitude of detector arrays would be required. They need to be optically coupled together without gaps. This can, in principle, be done with fiber optics bundles. Such a concept is described in more detail in Section III (Image Transportation Device).

III. CONCEPTS GENERATED BY BASIC RESEARCH EFFORT

A. Pop-up Periscope

1. Introduction

One of the objectives of the basic part of the present effort was to produce new concepts where MAO could be used and provide substantial advantage over existing technologies. One such concept deals with a pop-up device for observation of the surface of the sea. The design utilizes multiaperture optics (MAO) technology in combination with conventional single lens optics. The proposed design is actually also an extension of the design philosophy of the human eye which features a fovea capable of high resolution (20/20 vision), while the rest of the eye has only moderate resolution. The fovea has a radius of 1 degree, the rest of the field of view of the human eye delivers only a coarse image intended for attracting the attention of the gaze (FOV of the fovea) to an object of interest.

The proposed concept has a field of view of 7 degrees which has high resolving power and a field of view of 360 degrees with medium resolving power. The intention is to use MAO technology for the large field of view to pin-point the target and so make it possible to automatically acquire the target with a high resolution, single lens optics. The system will display the bearing in a digital form and will have a cursor which can be moved to the next target in case of multiple targets or if manual operation is desired.

The concepts anticipates a structure which resembles a pole which might be extended out of the water and withdrawn within one second or less. The optics used should fit in a cylindrical

structure of 1.5" in diameter and may have any length necessary. The acquisition time has to be one second or less. The stages to be considered are finding the target, acquiring the target with high resolution and withdrawing. For discussing the optical part we assume that the technology on how to manipulate the probe exists, we will consider only the design of the optical part of this probe and assume the periscope will be deployed for one second. We also assume the probe is attached to the boat, although at a later time it might be attached to an independent exploration vehicle. If attached to the boat it can be assumed that the direction of north is known and the display of the bearing will be relative to such a given input.

2. Description

Figure 33 shows an outline drawing of the proposed device. The MAO part consists of 30 detector arrays, each having 128 x 256 detectors. They are arranged in a staggered manner so that continuous coverage of the horizon can be accomplished regardless of the structure required for mounting of the detectors. · Figure 34 shows the location of an individual detector array chip behind the pressure window. Two lenses 3 mm in diameter having a focal lens of 6 mm illuminate each detector chip. These lenses are glued to the pressure window. Using 30 detector arrays, the 360 degrees of the horizon are divided into about 3,600 pixels or 6 minutes per pixel. The human eye can resolve about 1 minute per pixel and is therefore 6 times better, consequently the MAO part of the device will have 120/20 vision. The high resolution part of the proposed device consists of a camera lens of 35 mm
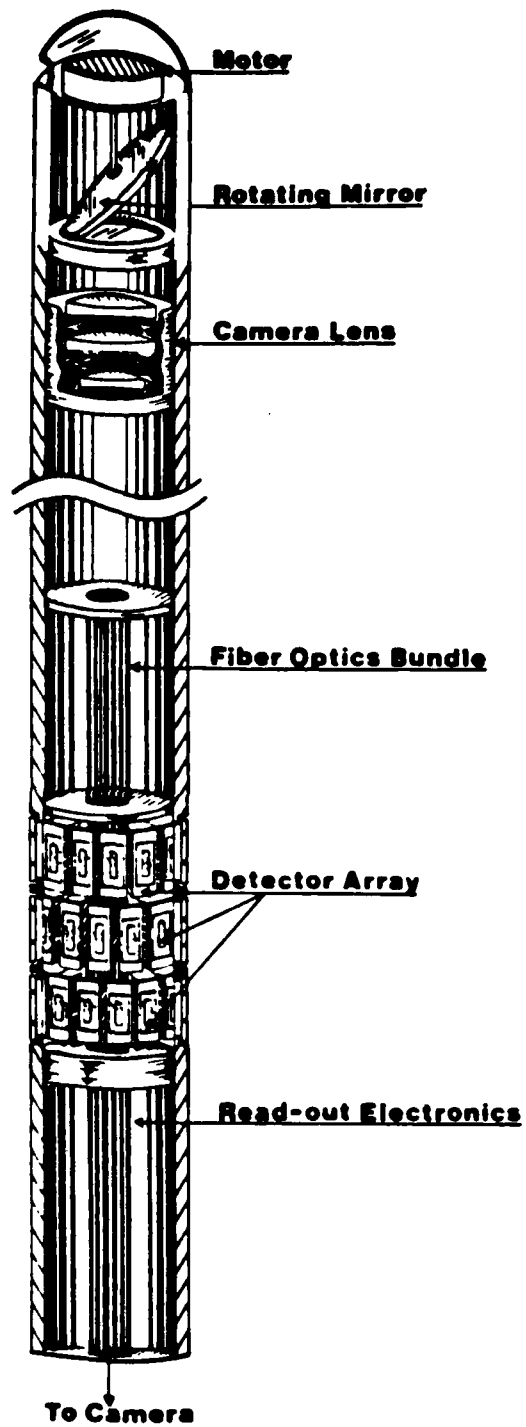
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Motor

Rotating Mirror

Camera Lens

Fiber Optics Bundle

Detector Array

Read-out Electronics

To Camera

FIGURE 33.   The Device
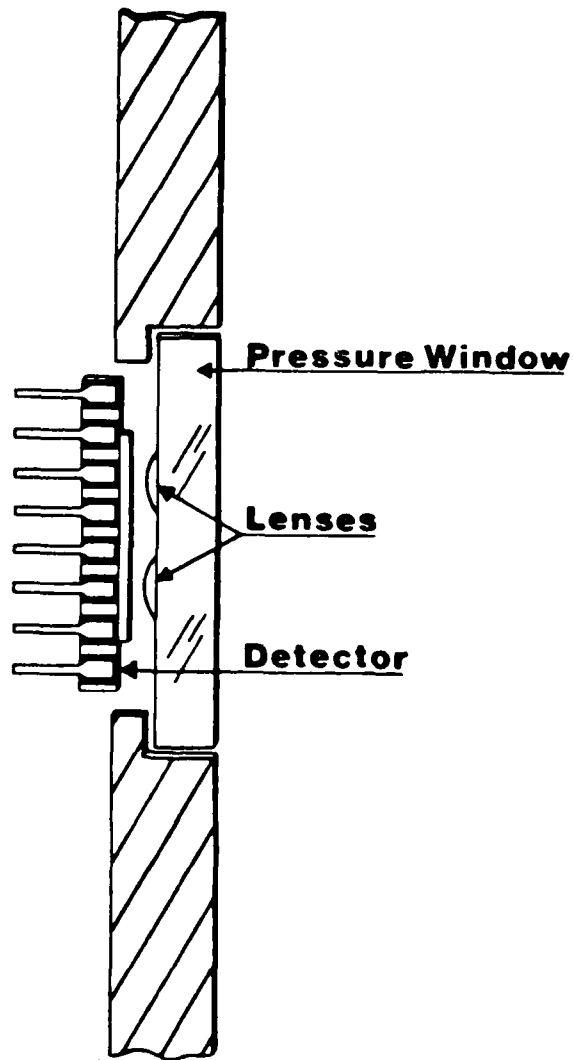
FIGURE 34. MAO Element

diameter and 200 mm focal length. It forms an image on a focal plane in which an array of fibers is located as a bare minimum. The fiber array may consists of 500 x 500 individual fibers, each fiber having a diameter of 6 micrometers. (For better resolution, larger cable see next section.) These fibers form a long fiber cable which leads down to the boat and is observed by a TV camera inside the boat. The polished end of the fiber cable will be either pressed against the photocathode of the TV camera or will be imaged enlarged on it.

The alternative would be a short fiber conduit which brings the image below the detector chips and a small TV camera which fits in the 1.5" probe mounted there. For the short option, a regular image conduit can be used which is commercially available. For the long cable which could be required to be 100 feet long, an image conduit would be too expensive, maybe not even available. However, 6 micrometer fibers are available in any length and therefore a regular fiber bundle would be used which is non-coherent and a new approach to read the output of this cable needs to be taken. This will be accomplished by, so to speak, cracking the code which the fiber cable, with its orientation of fibers imposes on the image. That means for each device built, a recognition matrix would have to be fed into the computer translating the address of one pixel of the image on the entrance plane to the address of the same pixel at the output plane of the cable. The code can be cracked by transporting a known image through the cable. Separation of the fiber optics cable into separate clusters is anticipated in case detector arrays are used instead of a TV camera tube, especially if one

eventually intends to use a 1000 x 1000 fiber matrix. In this
case more readily available arrays (e.g., 256 x 128) can be
clustered, without loss of information.

As also can be seen in Figure 33, there is a rotating 45
degree mirror which acquires the high resolution image and
delivers it to the 35 mm camera objective. The basic idea is to
rotate this mirror and acquire an image of the target at the
instant the mirror points towards the target. Depending on the
rotation speed of the mirror, this could be accomplished in a
high speed or a low speed version. In the low speed version, one
would have to wait until the mirror arrives at the target and
then acquire the image while the mirror keeps rotating. In the
high speed version, one would brake the mirror when it arrives at
the target and then acquire the image. The low speed version is
not very attractive since it has to stay in the order of 1/25
of a second on the target, and will spend a pro-rated longer time
viewing the rest of the horizon, which is not acquired.
Therefore it is proposed to use the high speed version. The
mirror will be turned on while still submerged. As soon as the
MAO part of the device detects the target, the mirror will be
stopped and the image will be acquired. In this case, there is
no limitation as to how long one takes to acquire the image.
Ordinarily it will be in the order of 1/25 of a second but that
might be different at night, there might be advantages in taking
more time. It is obvious that the rotating mirror will be on the
target almost instantly after the MAO part of the device has
identified the target.

3. Performance

The high resolution part could consist of a 35 mm diameter, 200 mm focal length camera lens which forms an image on an array of 500 x 500 fibers having 6 micrometers diameter. That means at a distance of 5 kilometers we have a field of view of 150 meters and a resolving power of 30 centimeters, meaning at 5 kilometers, two objects 30 centimeters apart will be recognized as two separate points. If one wants to compare this to a binocular, the human eye has one minute resolving power which translates to 1.45 meters at 5 kilometers distance. Therefore the high resolution part of the proposed device corresponds to about a 5X magnification. This magnification could of course easily be doubled just by using a 40 centimeter focal length lens instead of the 20 which is proposed, but we feel the 5X magnification is adequate to show the principle. The acquisition time for the TV camera is assumed to be 1/25 of a second. The MAO detectors will need about 50-100 milliseconds exposure time, of course they are "soaked" in parallel, therefore that is the acquisition time the total MAO device.

The basic problem which needs to be faced is to read several hundred thousand MAO detectors and do image evaluation to identify the target. This looks like a monumental task. Even with a large computer, it may take minutes instead of seconds. However it should be born in mind that MAO technology is different from regular image evaluation. First of all, each detector will return only 0 or 1 as a pixel, depending on the threshold set. The threshold will be set by hardware, and not by software. Only detectors which show intensity (or a lack of

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intensity--whatever is preferred) will be displayed. All other
detectors will be disregarded. For the proposed application, it
might be quite common that the target is darker than surrounding
background, especially if it is painted to be camouflaged. For
this reason there can be a double threshold applied. Simply,
this means a pixel that is considerably brighter than the
threshold given (or a pixel which is considerably darker than the
second threshold) will be displayed. A group of pixels above
threshold will be considered as a target if high spatial
frequencies are encountered in their distribution. This is the
extent of the image evaluation of the MAO device that will be
needed. In addition to this primitive form of image evaluation
some a-priori knowledge can be used to reject the sun as a
target. Since it is assumed that the direction of north is
known, the position of the sun also could be known and any pixels
which would fall on the sun within the MAO part can be
disregarded by design, thus preventing the device from
identifying the sun as a target.

Obviously one has to expect multiple targets. As described
so far, the device will only acquire the first target it
encounters while reading the MAO output from north to south to
north. However, all the targets will be displayed within the
resolution of the MAO device, therefore there will be a cursor
provided on the MAO disply screen which can be manually moved to
another desired target which can then be acquired with the next
rotation of the mirror.

4. Display

The proposed device will use one computer monitor as a display medium for the MAO device while the output of the high resolution device will be displayed on a second computer monitor. The high resolution output is fed from the TV camera into a "frame grabber". This component digitizes the high resolution image and stores it in a buffer memory. The digital image content is so available for image evaluation or display as is.

Since the MAO device will display the entire horizon in a low, but still useful resolution, the total output cannot be displayed on the monitor in detail as it is acquired. Therefore two display modes will be made available. One is the "survey mode" which will be ordinarily used. In this mode the computer will draw a line for the horizon, and a scale from north to south to north next to it. Any target encountered will be indicated by boxes of the size of the target, but not showing any details. There will be a circle showing the field of view of the high resolution device and the location where the high resolution device acquired the image. Figure 35 gives an indication of this synthetic display. There will also be a cursor which can be moved manually to a target which should be acquired in the next shot.

The second MAO display available will be the "detail mode". A 500 pixel wide x 256 pixel high display will be made of the region around the location indicated by the adjustable cursor. Thus, while the probe is submerged after a data acquisition "shot", the possible targets (indicated in the "survey mode") may
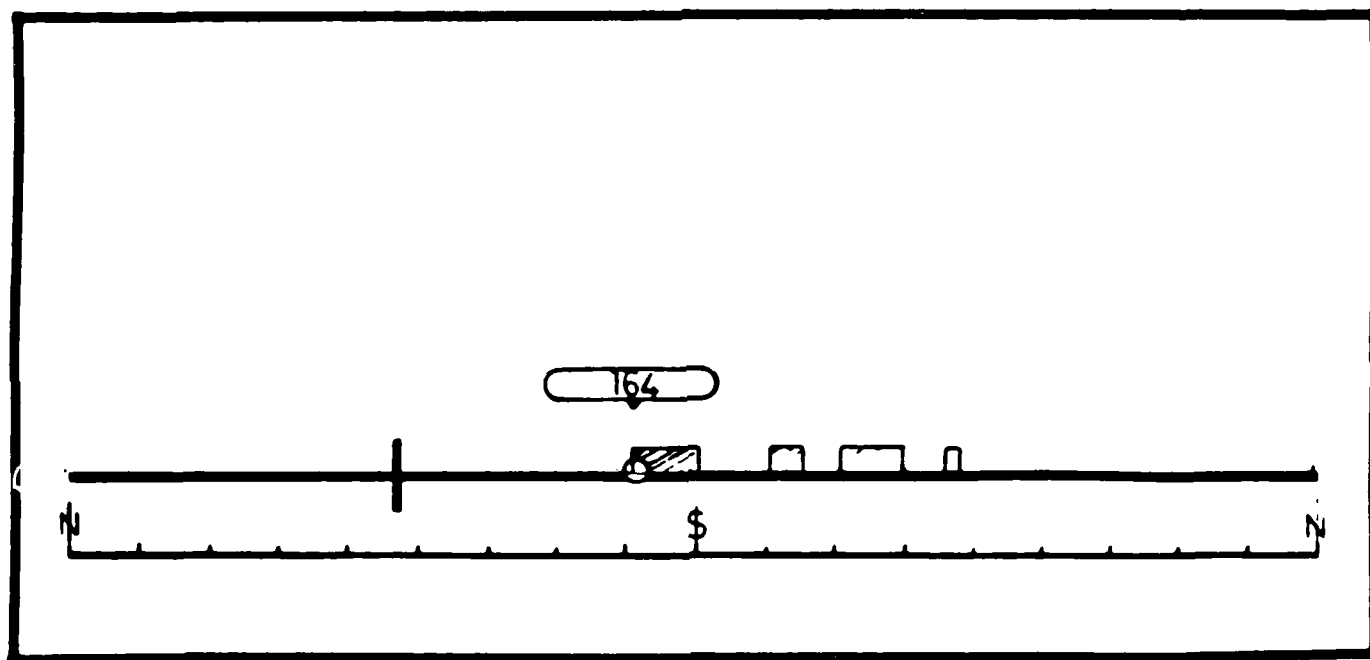
62

FIGURE 35. Display

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be examined in detail, of course only one target at a time. But

this allows the observer to judge if a particular signal is

important or not.

Figure 36 shows how the "detail mode" would show a part of a

ship, while Figure 37 shows how the ships display looks in

reality. As can be seen, the targets can be interpreted even by

looking at the MAO display.

Figure 36 covers a FOV of 22 degrees. The same target is

shown under an angle of 3.2 degrees in Figure 38. The more

prominent details of the target still can be recognized. It

should be noted that Figure 38 is a printer output, not

necessarily pleasing for the eye. Since there are 6 minutes of

arc per pixel, the whole target has 32 pixels in the horizontal

direction and about the same in the vertical direction. The

printer distorts the proportion of the target. The detector chip

itself is the inexpensive IS32A (Micron Technologies, Inc.).

This chip is only moderately sensitive and shows a fair amount of

noise. We reproduced the same viewing angle with a more

expensive CCD device (Texas Instruments) and obtained the display

in Figure 39. In both cases (Figures 38 and 39) the target is 32

pixels long and seen under an angle of 3.2 degrees. The chip

used for Figure 38 is probably adequate to detect the presence of

a target, while the CCD chip shows indeed some recognizable

detail. Figure 39 can be considered a binary image although the

CCD is capable to grey tone display, while the IS32A chip is only

capable to binary display.

For comparison, Figure 40 shows the target under the same

condition as Figure 36 was taken, but taken with the CCD and
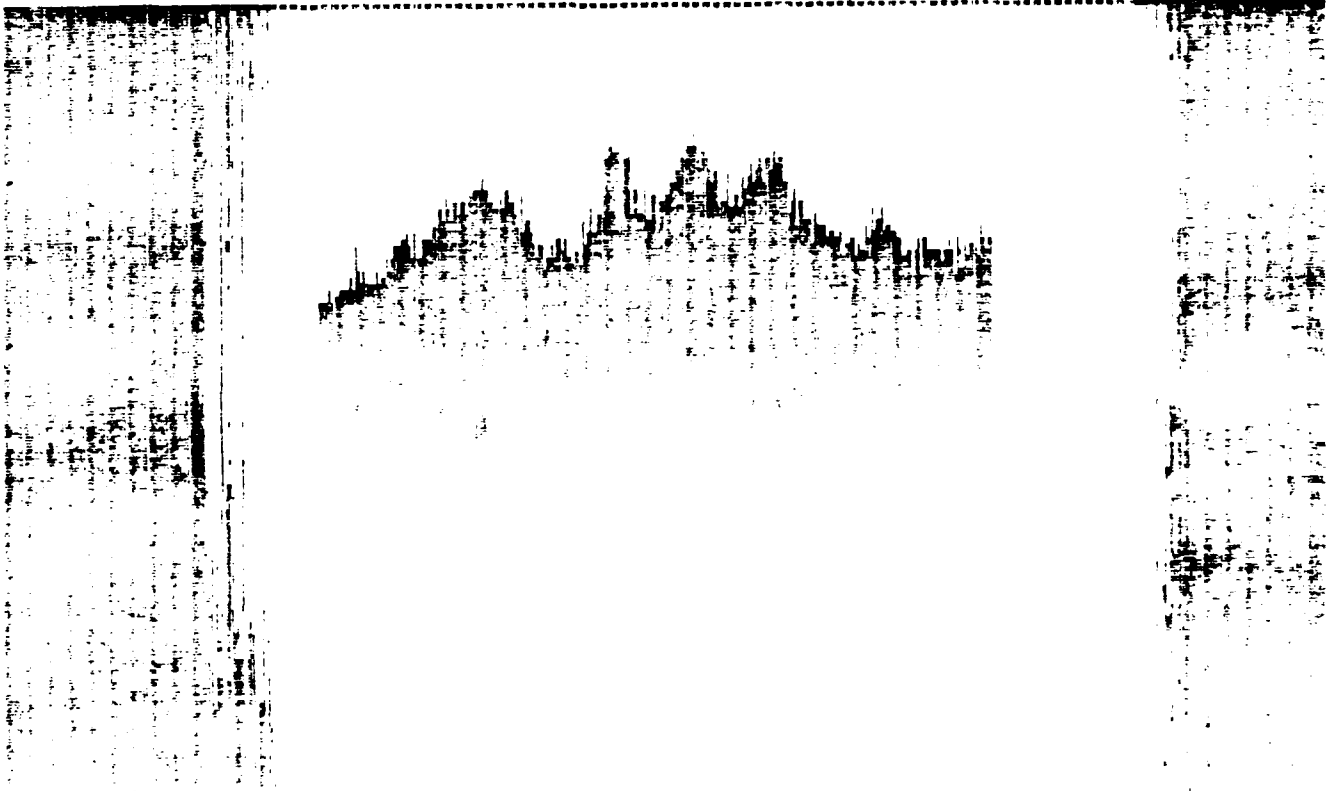
FIGURE 36. MAO Detail Display 22°

FIGURE 37. Picture of Model Used
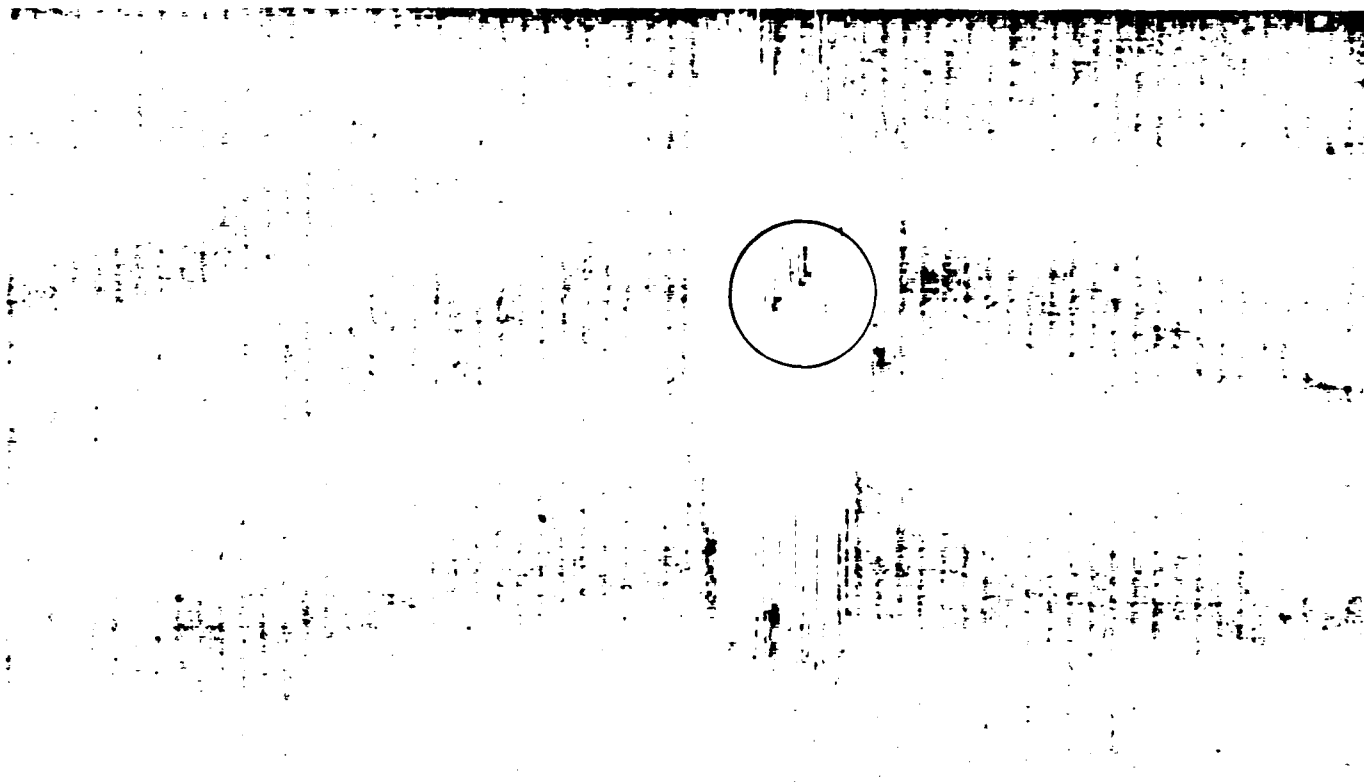
FIGURE 38. MAO Detail Display 3.2°
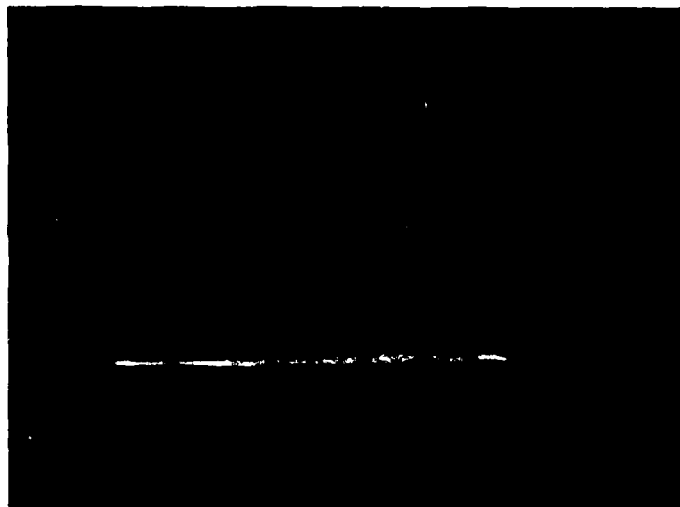
FIGURE 39. MAO Detail Display 3.2°, Using CCD Chip

FIGURE 40. MAO Detail Display 22°, Using CCD Chip

therefore now showing grey tones.

From the pictures, it can be seen that if one would consider a 6 minute per pixel resolution sufficient for the MAO device and one wanted to scan a band 10 degrees high for targets, one would need to acquire 360,000 pixels. Typical "soak" times vary for 0.1 to 10 milliseconds. The time required to read on detector array is in the order of 1/25 of a second. Since there are 30 detector arrays, they can be read in parallel and a target acquisition time of less than 1/5 second is certainly feasible.

This leaves sufficient time for the rotating mirror to be braked and the high resolution image to be acquired in a total time of less than a second.

B.   Image Transportation Device

1.   Requirements

With the advent of fiber optics technology, the opportunity of transporting optical images in fiber bundles became apparent. Such bundles must have a point-to-point relation between input and output of the fiber bundle. Such bundles are called "coherent bundles" and are in widespread use, e.g. in fiberscopes, etc.

There are, however, certain shortcomings which need to be overcome. The issues are:

1.   Size of the input and output area of the bundle.

2.   Diameter of the individual fiber used in the bundle.

Point 1.   Image Area: Since the location of each fiber has to be identical in the input and output plane, it becomes or the larger the total number of fibers is.

Point 2.   Diameter: The diameter of the individual fibers determines the resolving power of the system. The smaller the diameter, the better the resolving power is. The maximum acceptable diameter depends on the application.

Therefore, what are the requirements? Before we discuss this it may be advantageous to discuss resolution. One way to express it is in line pairs/mm. For example, if one wanted 100 line pairs/mm and one needed at least 4 fibers per line pair, then one needed a fiber diameter of 1/400 mm = 2.5 micrometers. A resolution of 100 line pairs/mm is achievable with photographic film. Standard fiber are 50 micrometers, therefore they produce a resolution of 5 line pairs/mm. A 50 micrometer fiber in barely visible with the naked eye. A photographic image, using this size grain, would not be acceptable. In principle, glass fibers could be drawn out to 2.5

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micrometer diameter, but the mechanical strength would be so low that handling of such a bundle would be very difficult, at the least.

If one wanted to compete with a 35 mm camera, one needed 36 x 400 = 14400 fibers per line for 24 x 400 = 9600 columns or 1.4 x 10^8 fibers altogether. If one wanted to compete with a large sheet film, e.g. chest x-ray, (maybe 10 x 10 in.) one needed on the order of 10^{12} fibers. These are, of course, fantastic numbers, but they illustrate the basic problem.

Therefore, why would one try to compete with photographic recording of images? There are several scenarios where this could be desirable. One could be where one wanted to take pictures in high radiation environments, e.g. inside a through port of a nuclear reactor. Here photographic recording is impossible. One could transport the image with relay lenses to a low radiation area and then take the picture photographically, or one can use a fiber optics bundle for transportation of the image. (Fibers which are radiation hardened are available.) Therefore, in this case one indeed competes with photographic recording. The fiber optics cable can be snaked around corners, while the relay lenses need a clear aperture. A fiber optic bundle would indeed be preferable if it could deliver the required resolving power. The same argument is true for any other periscope arrangement, e.g., for a submarine. Here it would indeed be advantageous to replace the relay lenses by fiber optics bundle, however the resolving power cannot be compromised.

Any application where observation of inaccessible locations are attempted, the fiber optics bundle is preferable. If the

location is so inaccessible that an optical relay is not possible, one does not compete with the photographic camera anymore, therefore, any resolving power is welcome. If a relay is possible, one has to be able to offer a resolving power comparable to the photographic camera.

What would a reasonable fiber bundle be? Obviously one would illuminate the input plane of the fiber bundle with an optical system of some sort. The wavelength of the light used and the diameter of the lens used determine the angular resolving power. Regardless of this, the linear resolving power, namely the diameter of the Airy disk, cannot be smaller than the order of magnitude of the wavelength of the light used. In the case of visible light we may approximate this by 0.5 micrometer. Considering lens imperfections, 2.5 micrometer is a good value for the Airy disk. The resolving power of the human eye in the fovea is considered to be 5 micrometers which translates to about 100 micrometers at reading distance (400 mm). Therefore, for an instrument used for visible observations, 50 micrometer resolution would be good enough. However to transport the image of binoculars (10X) 5 micrometer fiber diameter would be required. In other words, a fiber diameter in the 5-8 micrometer range would be a reasonable diameter to meet existing requirements. Consequently for 35 mm format (24 x 36 mm) a bundle containing a maximum of 3.5×10^7 fibers would be required.

If one had a coherent fiber bundle of such a size one could a graphic image of the exit plane of the bundle and about the same quality as if the camera

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had been located in the entrance plane of the bundle.

For some applications it would be preferable to replace the photographic film by a detector array.

Considering this we can now summarize the problems posed as follows:

1. How to manufacture a coherent fiber optics bundle of excessive length (e.g., 100') having a cross sectional area the size of the standard 35 mm format or larger.

2. How to manufacture a detector array having in order of 3.5×10^7 detectors of the size of 5 micrometers.

2. Proposed Solution of the Problem

We consider the above requirements as not fulfillable in the foreseeable future and therefore we proposed an alternate solution to the problem.

1. We propose to use a fiber optic bundle of random orientation of the fibers. This way any size bundle of any length can be assembled from standard 50 micrometer fibers. The image will appear to be "scrambled" at the output end of the fiber. We will unscramble the image by a computer program.

2. We propose to meet the 5 micrometer diameter requirement by cementing the fibers at the input end together for a short length and then drawing the rigid part out using a suitable amount of heat until the diameter of the bundle is reduced by a factor of 10. The appearance of such a fiber bundle is indicated in Figure 41. An alternate method would be to draw each individual fiber end down to 5 micrometers during the manufacturing process and cement these ends together to form the input plane. The appearance of such
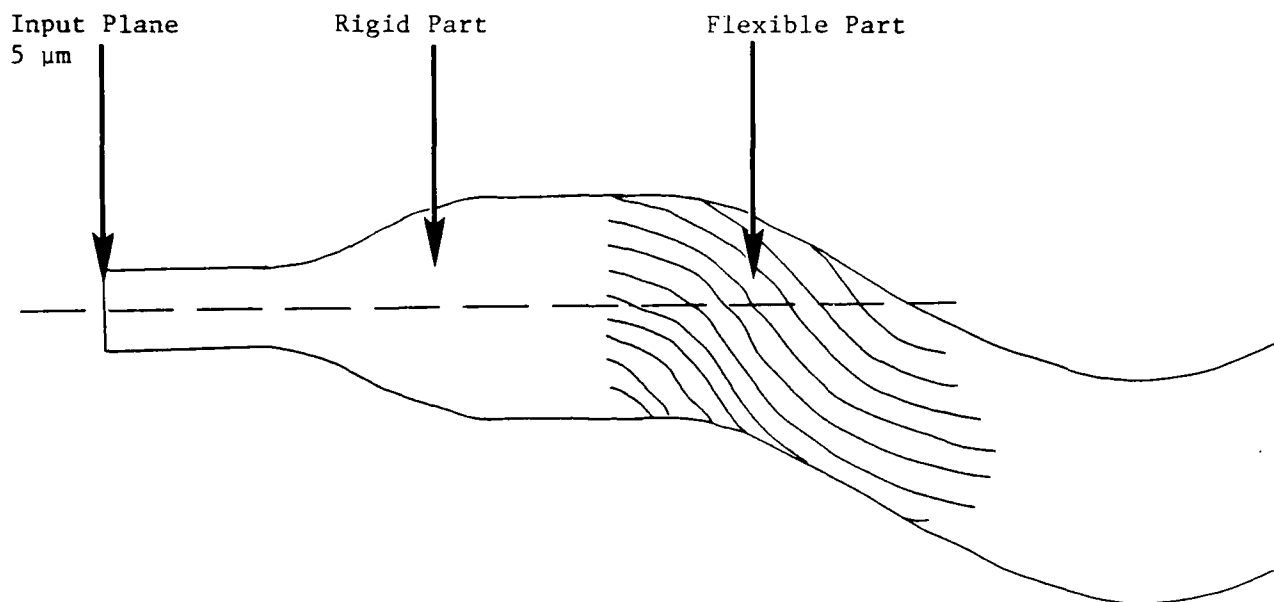
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Input Plane   Rigid Part   Flexible Part
5 μm

FIGURE 41. Drawn After Fusing

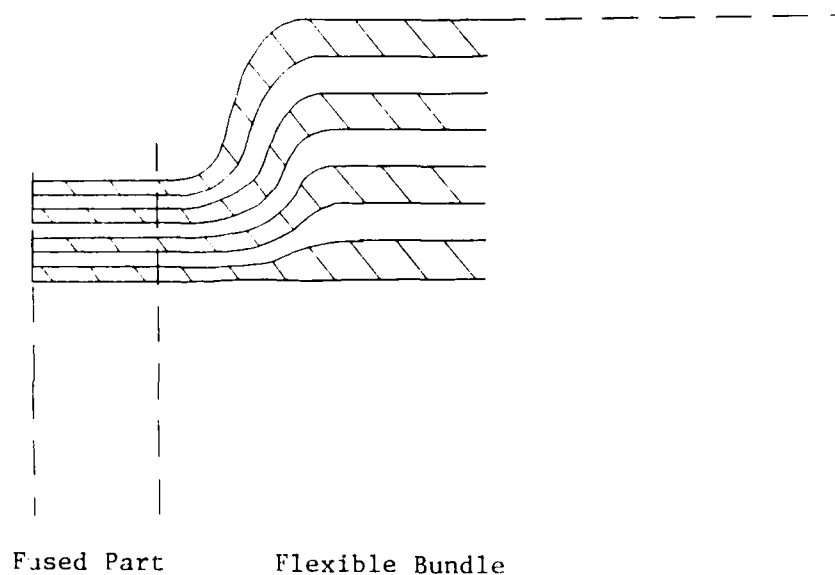Fused Part   Flexible Bundle

FIGURE 42. Drawn Before Fusing

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a system is indicated in Figure 42. If silica glass fibers are used the drawing process is established technology. If plastic fibers are used, a butt joint is used between the polished end of the 50 micrometer plastic fiber bundles and a short rigid conical piece of a drawn out (drawn from 50 --> 5 micrometer) input end.

3. We propose to meet the detector interface problem as follows. First we divide the output end of the fiber bundle into sub-bundles as indicated in Figure 43. The output end still consists of 50 micrometer diameter fibers. The number of fibers per sub-bundle will be equal to the number of detectors on available detector chips (e.g., 256 x 512). In this case a bundle containing 3.5×10^7 fibers at the input end would be subdivided into about 260 detector chips. The size of each individual detector on the array may be 50 micrometers in diameter, which is easier to manufacture than the 5 micrometer diameter detector. The separation between detectors may be of any size, however, for reasons which will become apparent below, we will make it also 50 micrometers.

Masks containing 50 micrometer holes (or slightly larger) will be manufactured. Such a mask will be used as art work to manufacture the detector chip. The individual fibers in the output ends of the sub-bundles will be fed into the holes of a mask and cemented in place as indicated in Figure 44. After polishing, the mask is aligned with the detector. This is accomplished by illuminating the input end of the total bundle homogeneously and checking for maximum signal output of the detector array.

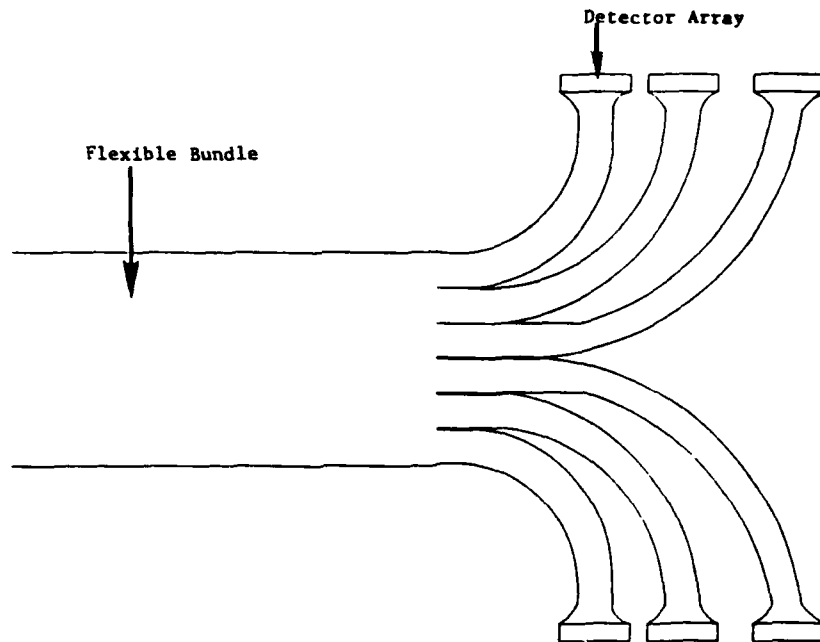The descrambling feature is accomplished by projecting a

Detector Array

Flexible Bundle

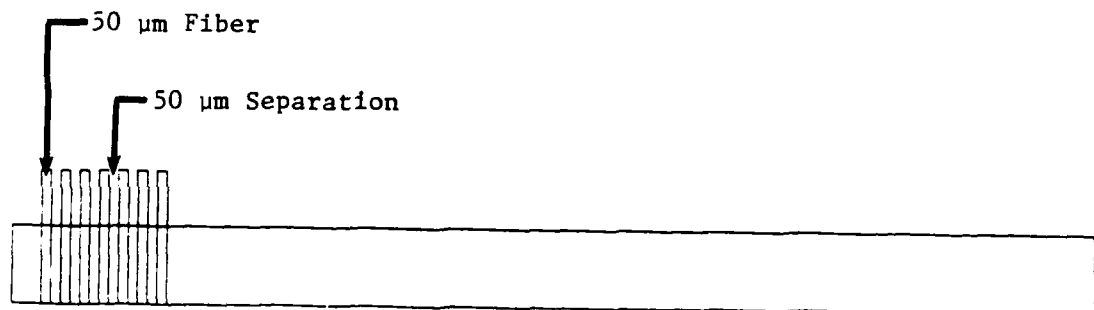**FIGURE 43.** Sub Bundles

50 μm Fiber

50 μm Separation

FIGURE 44. Mask

family of curves onto the input end of the total bundle.   The
curves may form an orthogonal grid with reasonable spacing.   The·
grid spacing can be varied at successive projections, or the lines
may be just shifted and the grid spacing may be kept constant.   In
either case, image lines and columns are defined at the input end
although the location of the fibers underneath is totally random.
Intersection of a line and column defines a pixel, the location of
which is identified as a rule by one detector output although there
will be cases where 2 or 3 detectors are involved.   The addresses
of these detectors are recorded on a diskette together with the
descrambling program.   The descrambling code is, of course,
different for each fiber bundle manufactured, meaning each bundle
would be calibrated in the factory.   It its of course possible to
computerize this procedure totally.

3.   Reduction to Practice

The manufacturing of the mask shall now be described.   We
developed this process and were successful in producing such
masks.

In principle 50 micrometer holes (about 2 thousandths of an
inch) can be drilled on a NC machine.   While this may be alright
for prototypes, the sheer number of holes would make this a very
expensive operation even for a NC machine.   The whole technology
will not take off if it does not lead to a reasonably priced mass
product.   An individual detector chip (about 260 are needed)
should cost in the tens of dollars including the mask.
Therefore, it is proposed to cast the mask, rather than machine
it.   The material used for casting could be a polyester or epoxy.

It should be black and it should not shrink. Also, it should

have good long-term stability. There are several materials

available which meet these requirements.

The mold required for the casting is constructed as follows.

A set of cylindrical steel pins about 1 inch long and another set

of cylindrical pins 3/4 inch long, all having a diameter of 0.002

in., are required. The total number of pins in each set is four

times the number of fibers to be mated to the detector chip.

Then a frame as shown in Figure 45 is manufactured. The frame has

to be precision machined, so that exactly 1024 pins (for a 512

detector row) fit to whatever tolerance they may need. The

fitting procedure is as follows. A slightly undersized slab is

machined as shown in Figure 46 and one row of 1024 one-inch pins

is glued onto it. Care has to be taken that the glue is spread

sufficiently thin that it does not get between the pins.

Rotation of the pins has to be avoided during the gluing process.

Once the glue has set on the slab, this assembly serves as a

gauge to machine the sides of the frame shown in Figure 45 so that

it will accept exactly 1024 pins. Once the frame has been

adjusted, one row of 1" pins, alternating with 3/4" pins, is

glued into it. After the glue has set, another row of pins 1/2

pin offset (dense packing) all 3/4" long is glued on top of the

first row. The next row again contains pins of alternating

lengths, and so on (see Figure 45). Then the frame is closed.

The next step is to destroy the glue by heating in an oven. The

back plate of the frame is removed and the back ends of the pins

are silver soldered in a hydrogen furnace oven. The front end of

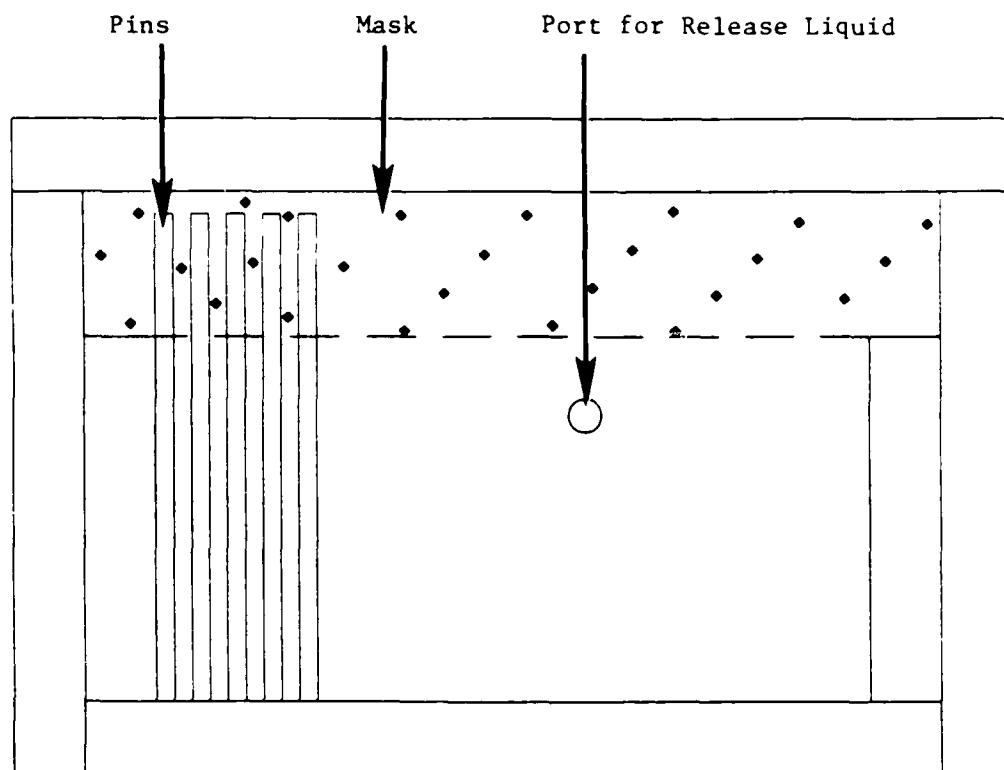the assembly is now the mold for the mask. A threaded plug on

Pins   Mask   Port for Release Liquid
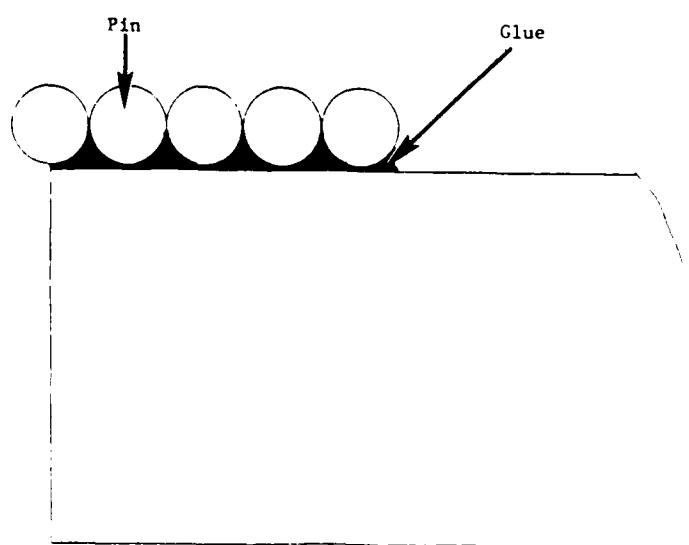
FIGURE 45.   Frame

Pin   Glue

FIGURE 46.   Gauge for Setting Walls of Frame

the side plate is now removed and fitted with a nipple to supply
a pressure release medium (e.g., water) to the mold for removing
the product after pouring. A suitable mold release should also
be used.

4.   The Pseudo-Lens

The transition from the 5 micrometer fiber plane to the 50
micrometer fiber plane (as in Figure 42) can also be accomplished
with a coherent fiber bundle. Such a device is already in common
use. Starting from coherent stock which is ordinarily used to
produce a rigid fiber optic image conduit consisting of soft glass
fibers, rigidly fused together into a rod one draws one end of
such a rod by a factor of 5-10. After the drawing process, both
ends are polished.

The resulting product still has a point-by-point correlation
between entrance plane and exit plane. The fiber ends on the
exit plane are now 5 micrometers (densely packed) in diameter
while the fiber ends on the exit plane are 50 micrometers (also
densely packed) in diameter.

This configuration we like to name "Pseudo-Lens". It acts
like a lens, although it is not a lens. If the entrance plane is
brought in contact with an object (e.g., a letter on a piece of
paper) its image will appear enlarged and sharp on the exit
plane, which can be viewed from any distance (no focussing
required). The pseudo-lens will collect all the light
the object emits (since it is in contact with it), while a lens
collects only a small fraction. The pseudo-lens is free from
spherical aberration, chromatic aberration, coma and

astigmatism. The output plane is automatically focussed as long as the input plane touches the object. A real lens cannot be brought so close to the object, it has to stay at least one focal length away.

However, like in a real lens, the light path is reversible. If one touches the object (e.g., letter on a piece of paper) with the exit plane, the image of the object will appear reduced by a factor of 10 on the entrance plane, again perfectly focussed.

5. Applications

a. Fiber Microscope

A microscope is an optical instrument featuring an objective having a short focal length. Since diameter of a lens and focal length are linked together by the f-number, this means also a small diameter of such an objective lens. If one is interested in a fiberscope with a diameter of not more than 2 mm, e.g., for insertion into arteries, then the above described technology is valuable. Figure 47 shows such a fiberscope using a flexible bundle. The objective lens is 2 mm in diameter. With f/2 a focal length, a focal length of 4mm is obtained. The image obtained cannot be larger in diameter than 2 mm due to the imposed space constraint. Using a flexible fiber bundle with 50 micrometer fibers, one can now transport this image with a 50 micrometer resolution, which is the conventional way, or one can transport a part of the image with a 5 micrometer resolution, which is the new way, as shown in Figure 47. Of course the other ends of the 50 micrometer fibers have to be mated to the detector array with the described mask in order to conserve the 5

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Mask

Detector
Arrays

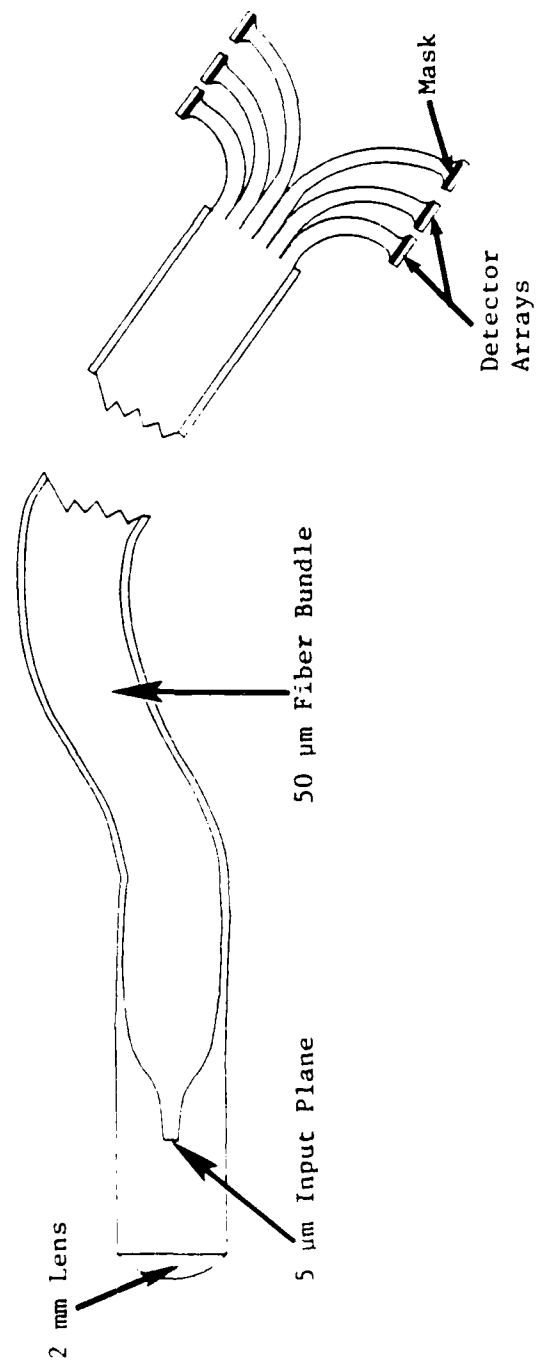50 μm Fiber Bundle

5 μm Input Plane

2 mm Lens

FIGURE 47. Fiber Microscope

micrometer resolution. (It is possible to just butt the 50 micrometer ends against the detector array, if one is willing to use smaller detectors, but we propose to use the mask eventually and use 50 micrometer detectors.) Coherent fiber bundles are expensive, therefore one would use an incoherent one and descramble the output of the detector array.

The human eye does not resolve 5 micrometers at reading distance, but rather 100 micrometers. Therefore, if the computer presents the information to the observer with such a resolution (meaning each 5 micrometer object point is represented by a 100 micrometer diameter dot on the screen), the image is, in fact, magnified by a factor of 20. That is the reason why this system is a microscope if the new way to transport images is used, but is not a microscope if the conventional way to transport images were used.

b. **Periscope**

In this application we assume that the required resolution on the input end of the fiber bundle is 50 micrometers, but a fairly large input plane is required (e.g., 24 x 36 mm). This infers a large lens having a long focal length. The distance the image needs to be transported shall be in excess of 100'. Figure 48 shows such a system. Due to the size and length of the fiber bundle, it needs to be flexible and incoherent. Typical numbers were given already in the previous section. What needs to be added here is that the approximate 260 detector arrays of course do not need to be arranged in one plane, they can be staggered and so fill the volume of a cylinder as indicated in Figure 48.
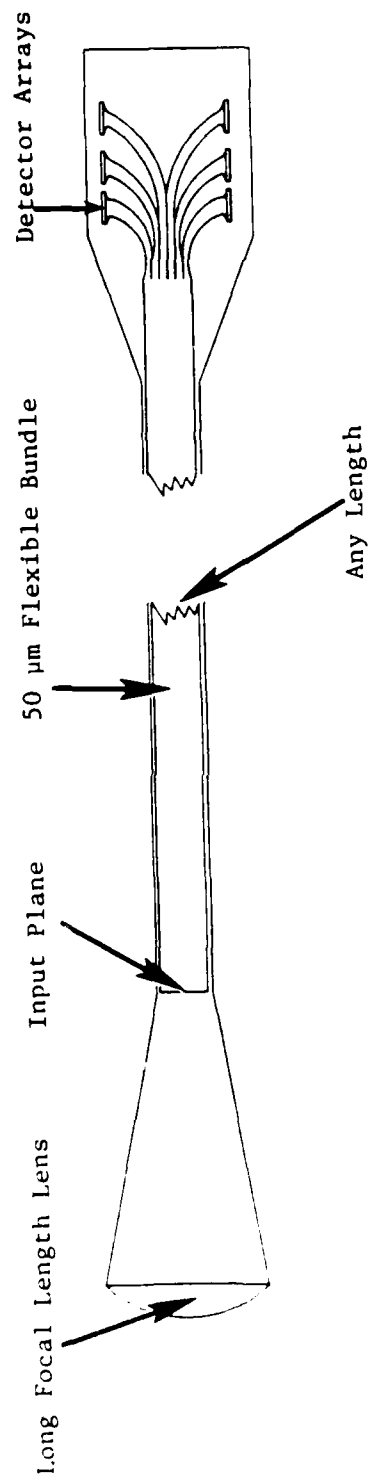
FIGURE 48. Periscope

In this way, the size of the receiving end of the system is still moderate. Also, the periscope tube can be modified so that it is no longer one rigid tube because lenses will no longer have to focus over it's entire fixed length. Instead of a tube, it could be a flexible cable which can be rolled up on a drum.

c. Insect Eye

Assume there is plenty of illumination and one wanted a sentry which looks in all directions simultaneously (e.g., on a carrier for display of approaching aircraft). Here 10X magnification would be appreciated, meaning one wants 5 micrometer resolution on the input plane. A roving (scanning) camera may be to slow to cover the total hemisphere. Therefore, an arrangement as indicated in Figure 49 can be made. A relatively small lens (2 mm) can provide the specified resolution, therefore the resulting "dome" is still of rea   size. The number of lenses required is very large and consequently so is the number of detector arrays req   read out. Also it would be impossible to displ   hemisphere in one piece.

Therefore one would resign
fraction of the detector arr
target in it. Also n
fields of view
disappear
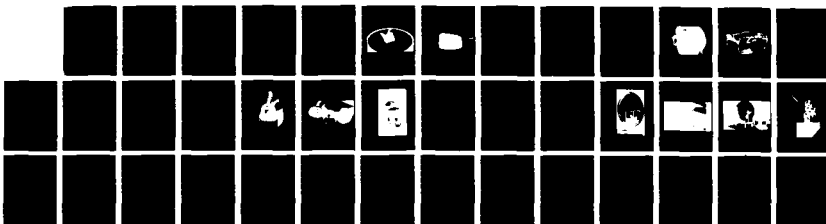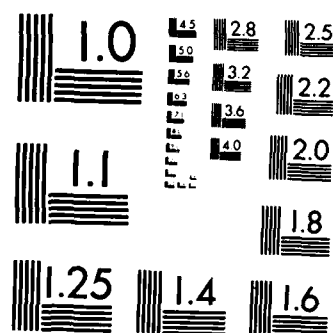
MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963-A
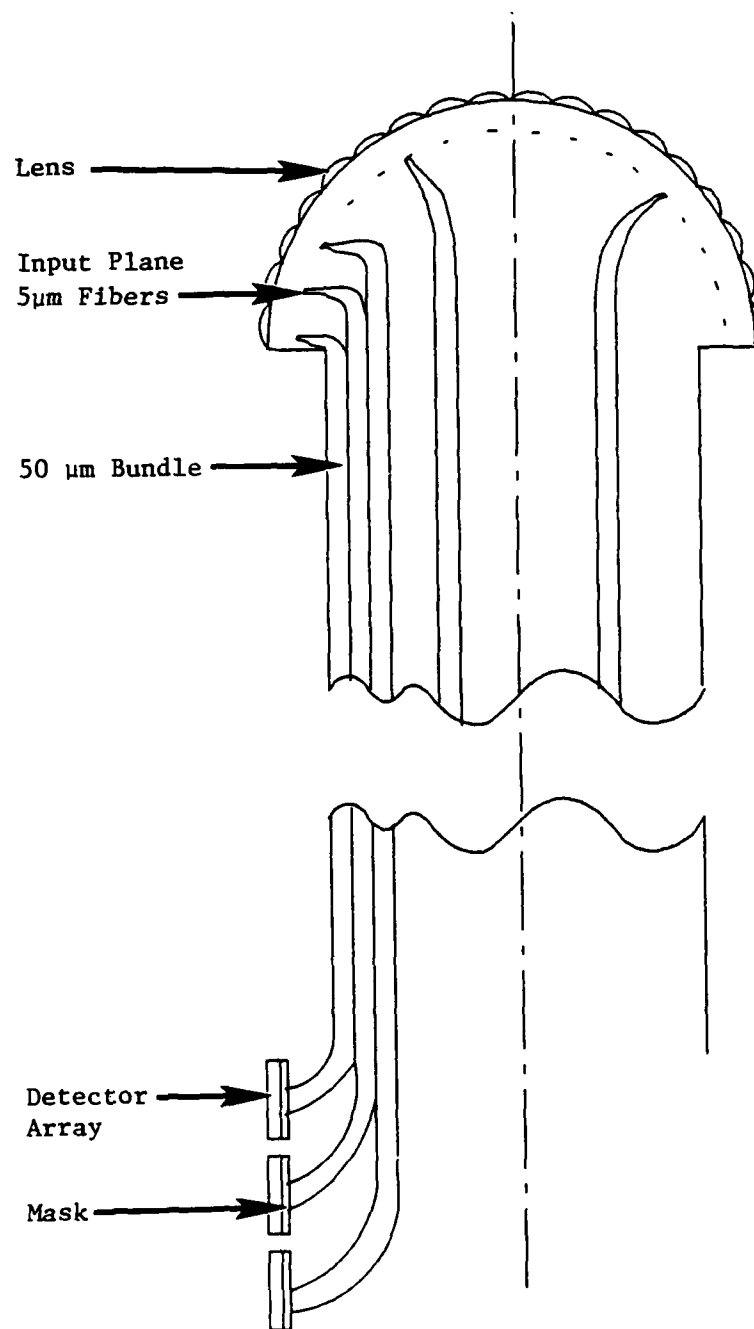
FIGURE 49. Insect Eye

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stares at a certain section in space, the position of the target

is easily obtainable and can be displayed on the screen.

Multiple targets can be displayed on multiple screens. They will

be activated as soon as the system finds an object, meaning high

spatial frequencies, which are ordinarily not found in the sky.

IV. APPLIED RESEARCH EFFORT

A. General Remarks

The theory governing the devices described in the following section was already explained above. Therefore the descriptions following here are only intended to describe the devices and their performance.

The original intent was to pick two applications of MAO and demonstrate that indeed a functional device can be based on this. We actually developed three devices since we wanted to demonstrate, the wide field of view of the MAO device more drastically.

B. Mask Fabrication

Masks which contain either conical or cylindrical holes were used to convert detector arrays into MAO devices. Their performance was already described in Section II, 2 (Non-Imaging MAO).

The mask fabrication was based on similar principles as pointed out in Section III, 2. Therefore, the basic drawings do not need to be repeated here. The difference here is that in Section II, 2 (Non-Imaging MAO) a mold used for cylindrical holes was described, while here conical holes are preferred.

The main change is that the cylindrical pins are now converging into a sharp point. After the product is released from the mold, both sides need to be sanded until entrance and exit holes of the cones have the correct size. The entrance holes, which are the larger ones, become smaller by sanding, while the exit holes become larger by sanding.

After the mask has been sized properly, it is bent over a sphere with the addition of heat until the desired inter eyelet angle is achieved.

Since not all moldable materials are also thermoplastics, an alternate method of mask fabrication was devised which is suitable for non-thermoplastic castable materials. Here the pins need to be aligned under an angle which corresponds to the desired inter eyelet angle. Because of this angle, the pins need to be individually withdrawn, after the mold is poured and set. The main problem was to hold the pins in the proper location until a holder is poured around the pins which fixates each one in its proper place. This was accomplished by mounting two filter elements (screens) at precise elevations. Figure 50 shows a photograph of the pins in their holder. Only the very top of the pin assembly will be used to form the mask. Finally, Figure 51 shows a photograph of a typical mask. This particular one has an entrance aperture of 300 micrometers and an exit aperture of 100 micrometers. For comparison a typical pin is shown in the figure.
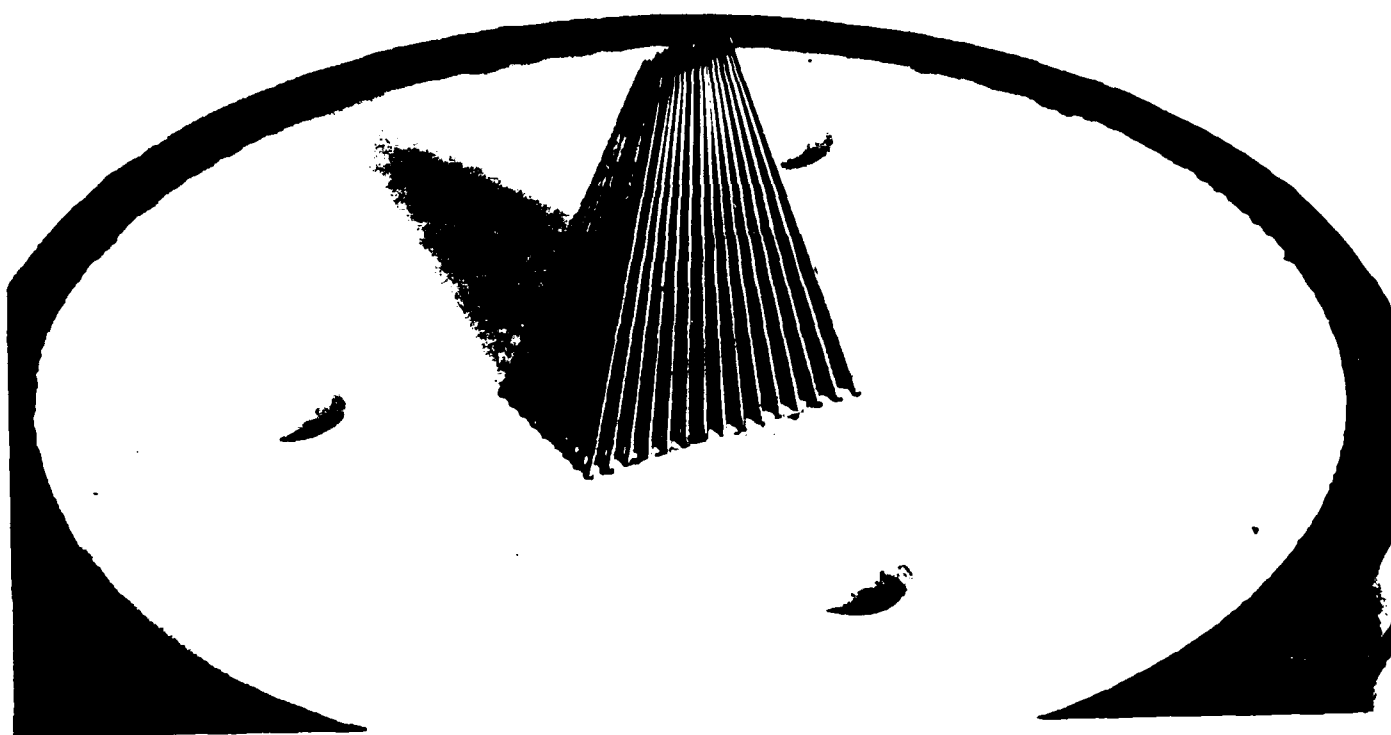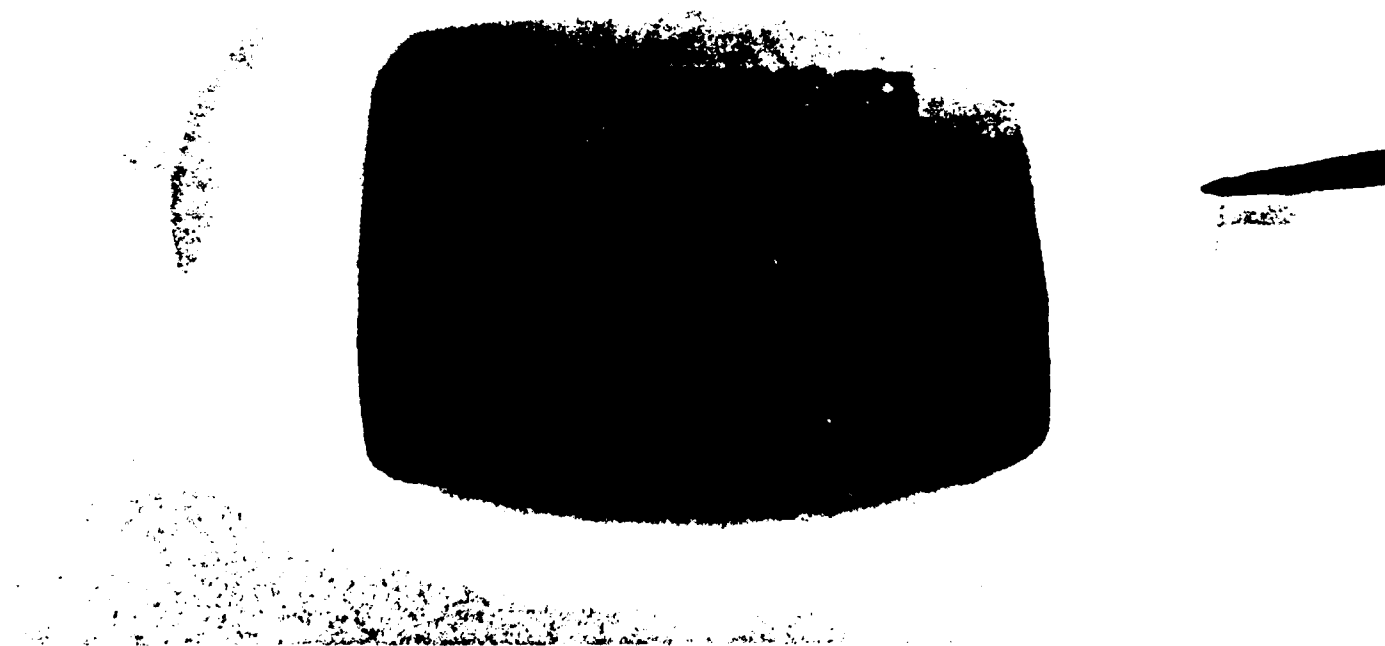
FIGURE 50. Photograph of Pin Assembly

FIGURE 51. Photo of Typical Mask

V. PRODUCTS RESULTING FROM APPLIED RESEARCH EFFORT

A. Pupil Tracker

1. Introduction

The rapid, accurate measurement of eye position has a broad range of applications in many experimental situations. Eye fixation patterns, for example, have been used in cognitive psychology to examine and quantize such activities as reading, decision making, picture processing, and picture memory. Similar measurements have been used to evaluate television commercials and advertisements in the printed media. Such automated measurement devices could also have great value in weapons-pointing applications or robotic vision systems.

The particular eye tracker described here is the prototype for a variety of such devices. It is mounted on an ordinary eyeglass frame which in turn is connected to a microcomputer. It illuminates the eyeball with infrared light emitting diodes (LED's), images the pupil, and calculates from the image a two dimensional location of the center of the pupil. This location is available at one of the microcomputer output ports and is updated over one hundred times per second. This particular design was based on specifications determined by the Orlando Naval Training Devices Center for use in a Flight Training Simulator. The simulator consists of a large sphere at the center of which is located a complete cockpit. The aviator-trainee sits at the cockpit and observes the inner surface of the sphere upon which are projected computer generated images. The computation of the images with sufficient speed and detail is a major task. The task is significantly eased if the direction of vision of the aviator-

trainee is known at all times--the highly detailed portion of the image may be reduced in size. The desired performance of the pupil tracker is a sampling rate of 120 Hz or higher at an accuracy of one-half degree.

A number of eye tracking instruments have been invented and used in the past. These include: (a) a small hole in the scene observed by the patient through which a camera might record eye positions, (b) an infrared projection lamp which illuminates the eye, producing first and fourth Purkinje images, the positions of which are measured with an optical system and photodetectors, (c) television recording of the corneal reflection of a light source, and (d) photodetector measurements of iris scleral limbus reflections. Some of these devices are commercially available, and some have the capability of measuring pupil diameter as well as eye position, but they are all relatively large and expensive. The device described here is small, light, fast, and much less expensive.

2. Performance Criteria

a. Accuracy

The most important performance criterion is accuracy, defined as the range of eye positions which will be observed if the eye repeatedly fixates on the same object point. The desireable value for cognitive psychology experiments is generally taken as one-half degree. Better accuracy may not be meaningful in any event since the angular width of the fovea (about two degrees) permits a one-half degree range in the fixation point.[9] (Rashbass, 1961).

b. Speed

The literature indicates that eye position sampling rates of 25 to 100 Hz are adequate for most purposes. The prototype described here was designed for a sampling rate of over 120 Hz with an Intel 80386 microprocessor based microcomputer (e.g. Compaq Deskpro 386).

c. Sources of Error

The position of an eye relative to a fixed scene is determined by (1) head movement, and (2) eye rotation. Generally, other eye trackers have attempted to remove head movement problems by fixing the head[10] (monkey experiments, Vaughan, 1975), or by attempting to fix the head with the use of head-chin rests[11] (Clark, 1975) or a rigid bite-plate[12] (Russo, 1975). Alternatively, head movements may be detected and measured relative to a fixed field[13] (Young and Sheena, 1975). Head movement is usually the largest single source of error, since the transverse motion of the head of only 0.17 mm has been shown to be equivalent to a one degree eye rotation [14] (Ditchburn and Ginsborg, 1953).

Other sources of inaccuracy include mechanical drifts and backlash, analog signal drift or nonlinearities in the device.

3. General Description of The Eye Tracker

The eye position tracker described in this report is shown in Figure 52 and consists of: (1) fourteen light-emitting-diodes (LED's) mounted evenly around an eyeglass frame, (2) a MAO device which produces an image of the pupil of the eye upon an optical RAM (random access memory) chip which is coupled to (3) a digital

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A

FIGURE 52. Eye Tracker

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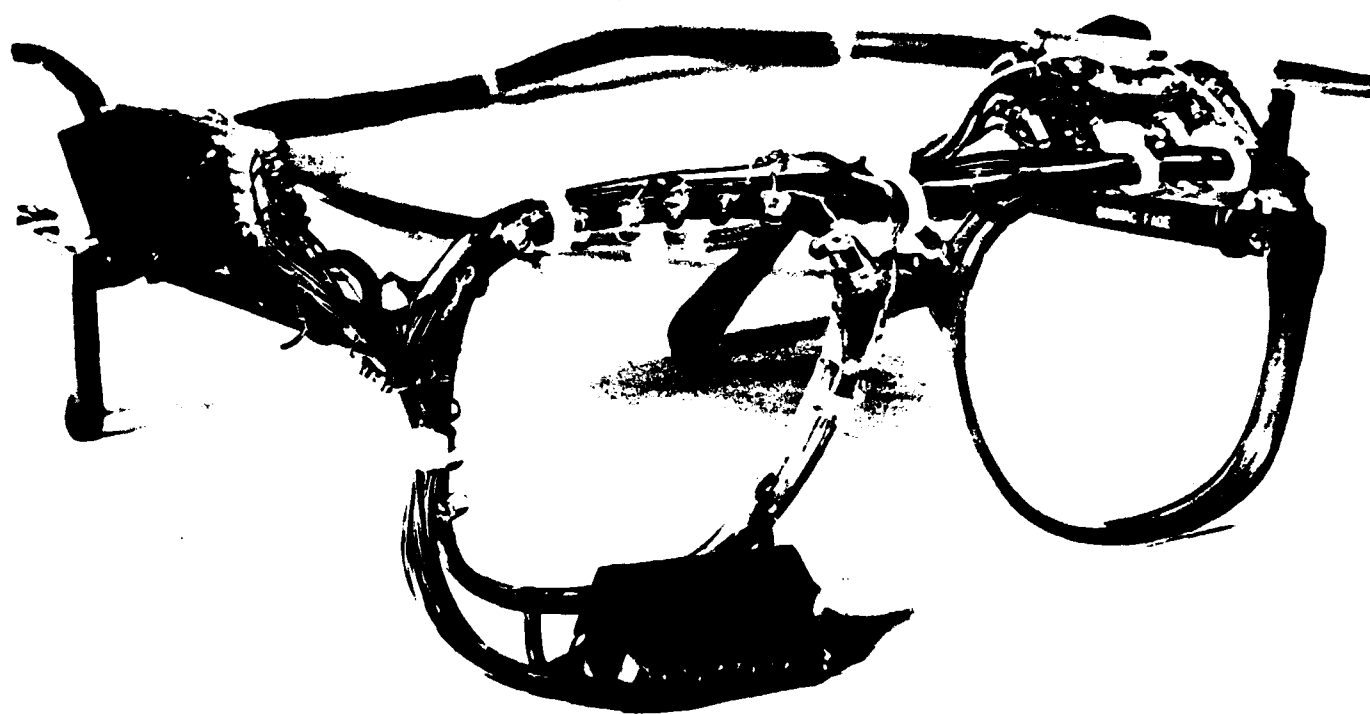
B

Figure 52. Eye Tracker, continued

electronic board mounted in an IBM microcomputer. The problem of head movement is thus separated out of this eye tracker system. The image of the pupil appears as a totally black disc on a fully illuminated background. The device requires one or two milliseconds to acquire sufficient photons to turn 'on' the proper bit locations on the optical RAM, several milliseconds to transfer the data to the computer and locate the center of the pupil. The eye position sampling rate with an IBM AT computer (nine MHz clock) is above 100 Hz with a 3.0 mm diameter pupil. The accuracy is better than or about equal to one-half degrees. Greater accuracy is achievable by reducing the sampling rate or by using a computer with a higher clock rate (e.g. 20 MHz Compaq 80386 based personal computer). With the (faster) computer, accuracies better than 0.5 degrees at sampling rates above 200 Hz should be easily achievable.

4.   Detailed Description of the Prototype Eye Tracker

(a)   LED eye illuminators

Fourteen type OD-8830C gallium aluminum arsenide infrared (880 nm) LED's (Opto-Diode Corp.) are mounted at approximately equal angular intervals around the rim of the eyeglass frame. Each operates at 50 mA at five volts and provides 8.0 mwatts optical power output at the eye. The sclera (white) of the eye has high reflectance for the infrared radiation. The iris and limbus (sharp border between iris and sclera) have lower reflectances. The pupil, however, absorbs the infrared photons and re-emits a portion as an approximate beam directly to the front of the eye. The optical system thus obtains a large number of photons from the iris-limbus-sclera and very few from the pupil.

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(b) Optical System

The optical system consists of a small (3.0 mm diameter, 4.5 mm focal length) biconvex, simple lens mounted on the bottom of the eyeglass frame at a distance of 5 to 6 mm from IS256 optical RAM chips produced by Micron Technology Inc. The chips are connected to the microcomputer with a 37 wire data bus and power supply cable connected to an internal plug-in card. The operator utilizes a menu to determine the 'bias' level (how many photons must be received by an individual 'bit' on the chip to turn it 'on'). The system then repeatedly traverses the data acquisition cycle of : (1) accumulating photons on the optical RAM chips, (2) transferring the data (image) to the microcomputer, (3) determining the center point of the pupil as a two dimensional address, (4) outputting the address, (5) resetting the optical RAM to zero. The IDETIX system consists of (1) the optical RAM chips, (2) the cable and data acquisition card, (3) the (assembly language) routines which transfer the data (image) to a set of memory locations in the microcomputer. The algorithm to find the two dimensional address of the center point of the pupil (and send that information to an RS-232 output port) was written in compiled BASIC by RTS Laboratories Inc.

The algorithm for locating the center of the pupil requires a measurement of the pupil diameter at regular intervals (once per second for the prototype). This information is continuously updated and available at a particular computer memory location. The algorithm which accomplishes the updating is a compiled BASIC subroutine to the main program.

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(c) Data Acquisition and Processing Algorithms

(i) Startup

When the computer is turned on with the self-booting IDETIX program floppy disc, a menu is displayed which allows the operator to (a) change any exposure parameters desired, (b) view whatever the optical system is currently 'seeing', or (c) operate in the automatic tracking mode. Normally, one starts with the "viewing" mode by inputting 'R'. The pupil may, or may not be visible on the display screen, depending on the eye position. The operator may use the cursor control keys to pan around in image space until the pupil is seen on the display. The patient can assist by keeping his eyes reasonably fixed.

(ii) Tracking

The operator then inputs 'T' to switch to the automatic tracking mode. The program finds the initial pupil diameter, then repeats the data acquisition cycle over and over, sending the two dimensional address of the center of the pupil to an RS-232 output port each time. Every 100 frames, the pupil diameter will be re-measured and stored. The flow diagram of the tracking algorithm is shown in Appendix A.

5. Performance of the Prototype

The prototype eye tracker has been tested on a model head with artificial eyeballs and also on the authors. The artificial eyeball had a pupil diameter of 3.0 mm and the pupil center was measured with an accuracy range of about 0.35 degrees at a rate

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of 100 Hz using a 9.0 MHz clock IBM AT computer. (With a 4.77 MHz Fountain Turbo XT IBM clone, the sampling rate was limited to about 25 Hz).

The prototype was also tested on volunteers at RTS Laboratories Inc. with varying levels of illumination in order to vary pupil size. In all cases, the sampling rate was nearly independent of pupil size at 100 Hz (with the 9.0 MHz clock IBM AT which was equipped with an 80287 coprocessor chip). It is estimated that a sampling rate $\geq$ 200 Hz is easily achievable with an 80386 based microcomputer.

B. Surveillance Look-Out

Surveillance devices are widely used as part of many security protection systems in military installations, factories, laboratories, banks, or retail shops. They may be as simple as infrared beams, which, if interrupted, trigger alarms. They are often found as fixed television cameras which may be triggered by changes in the image to sound an alarm or alert. If a human being is present to monitor the images, they may consist of fixed or panning television cameras.

The prototype surveillance look-out device constructed at RTS Laboratories Inc. and described here was intended to utilize the technology developed in the course of this contract to produce a surveillance monitor which was compact, light, rugged, less expensive than other surveillance devices, and could be battery operated to provide independence from A.C. power supplies. It was also designed to provide viewing over an entire hemisphere (two-pi solid angle) without panning (monitor movement) or the distortion of fish-eye optics.

The prototype monitor is shown in the series of photographs in Figures 53 and 54. It consists of (1) sixteen lenses (3.0 mm diameter, 7.0 mm focal length) mounted at equi- angular distances on a 5.0 cm diameter hemisphere, (2) sixteen coherent fiber-optic light guides to transmit the images produced by the lenses down to (3) the optical RAM chips mounted in a 5.0 cm long tube connected to the hemisphere. The entire monitor is thus only 5.0 cm in diameter by 8.0 cm long. It might be mounted, for example, in the ceiling of the space to be protected and will produce an image of the entire 2-pi solid angle.

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FIGURE 53. Surveillance Look Out, Assembled

A

FIGURE 54. Surveillance Look Out, Disassembled

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B

Figure 54. Surveillance Look Out, Disassembled, continued

The monitor is connected by a signal cable to an interface multiplexor which is in turn connected to the controlling microprocessor. The multiplexor accepts data from each of the optical RAM chips in turn and stores that data in computer memory.

When the entire (current) image has been acquired, the current image is compared pixel by pixel with the last previous image. Any significant number of differences between the two images indicates the presence of an intruder (or other condition which might require investigation). If no significant differences are noted, the algorithm t'en clears the previous image, transfers the current image to the memory location of the previous image, and instructs the multiplexor to acquire another (current) image.

The optical RAM chips used, IS256 (Micron Technology Inc), are sensitive to a wide range of wavelengths. The area to be monitored may be provided with infrared illumination or visible light illumination (or both). The multiplexor/microprocessor is designed for battery operation so that it cannot be disabled by interruption of the A.C. power supply and provides a clear alert if the illumination changes significantly or if successive images show significant changes.

C. Perimeter

The perimeter is a device to measure a person's field of view. Certain eye diseases, especially glaucoma, cause variations in the shape of the field of view. A perimeter test is therefore a means of diagnosis for these diseases. The perimeter described here is meant as a screening device. In contrast to the perimeter presently in use, which takes up to 30 minutes for one examination,

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the perimeter developed under this effort allows instant recognition of seeing deficiencies. It is therefore practical to use it as a screening device for a large number of people, e.g., recruits, which hitherto could not be done.

The conventional procedure is to place the patient in front of a hemisphere in such a way that his eye is located at the center of the hemisphere. The patient is asked to fixate his gaze at a certain point on the inner surface of this hemisphere. At that point, the objective of a telescope is located in a way that the physician, looking through this telescope, is able to observe if the patient is indeed fixated. Then the patient is shown a lighted point at a random location on the inner surface of the hemisphere. If the patient sees the point, he pushes a button which signals either the physician or a computer to accept the event as a data point. The field of view has to be pieced together point by point. Depending on the type of perimeter and depending on the fact whether the procedure is manual or computerized, the examining time can be as short as 10 minutes or as long as 30 minutes.

Aside from this it requires cooperation of the patient, which can not always be assumed. Even so, the level of cooperation will diminish in time, therefore a device suitable for mass screening will need to work on a different principle.

Another aspect is that with the conventional perimeters the patient's word has to be accepted. There is no way to check whether he actually sees or does not see the point shown. This is important in court cases, where a person may claim he does not see while in reality he does.

Both shortcomings are overcome by the device developed under

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the present effort.

Figure 55 shows the perimeter developed. It consists of a hemisphere of the same size as usual and it features a special projector which is capable of projecting a pattern inside the hemisphere, filling the total hemisphere with visible structures, rather than projecting only the usual one point.

The projected image could consist of a family of curves, and if there is a seeing deficiency, parts of the curves would be invisible to the patient. Of course, one can project curves having gaps in it in the first place to verify cooperation of the patient.

Once the patient is properly fixated, it will take, for the patient, only a short look to determine whether he has a seeing deficiency or not. The fixation of the patient is determined automatically by a motion detector which was developed for this purpose. Figure 56 shows the photograph of the patient's eye as it appears on the monitor (visible in Figure 57). On this figure, four points can be seen inside the pupil of the patient. These points can be adjusted by the physician to fall inside the pupil. He will do so after looking through the telescope, which has a cross hair and he is satisfied that the center of the pupil coincides with the cross hair. After the four points are set, an alarm will sound if any one of the four points wanders outside the pupil.

The mini-projector which is capable of illuminating the total inside of the sphere is a MAO device of the imaging type. It is shown in Figure 58 separately. It consists of 27 projection heads, or eyelets. Each lens has a 3 mm diameter and a focal length of 4.5 mm. Instead of detectors there are 30 micrometer diameter

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FIGURE 55. Perimeter Hemisphere With Special Projector

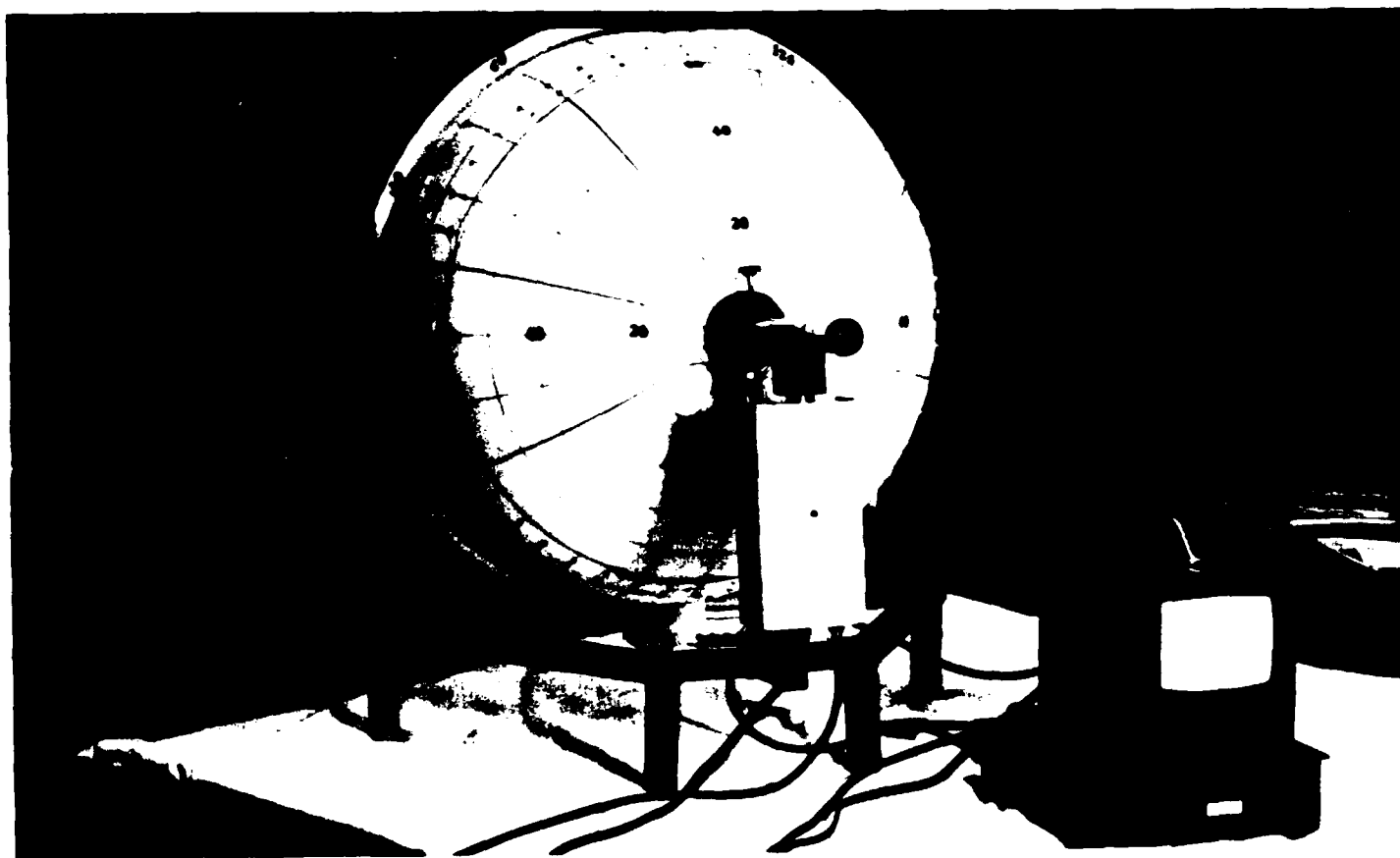**FIGURE 56.** Photo of patient's eye as it appears on monitor

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FIGURE 57. Perimeter from the back, showing monitor camera and motion detector

FIGURE 58. Mini Projector

fibers filling the image plane area of each lens for about the size of the lens. Each image plane is covered with a small rectangular mask delineating the projected area so that a smooth overlap of neighboring areas is achieved.

The other end of the fibers terminate on the surface of the slide to be projected. Other than proper illumination of the slide, there is no further optics necessary, since the fibers touch the surface of the slide.

In Figure 57 the telescope, camera, monitor and the motion detector can be seen. Also, in Figure 55 a ring of infrared LED's can be seen. With these LED's in operation, the patient's eye is sufficiently illuminated, without the patient seeing any red glow. Therefore perimetry can now be performed at any ambient light level starting from complete darkness to bright daylight.

The motion detector itself is a device used in conjunction with a low light level infrared sensitive television camera to ensure eye fixation during the course of an examination of the eyes' field of view.

This device checks for eye fixation by comparing the luminance level at four points within the camera's video picture of the eye against a luminance level that previously had been preset when the eye was determined to be fixated and the four points were adjusted to be just within the pupil of the eye. The four points are equally spaced around the edge of the pupil of the eye. Therefore any movement of the eye would cause at least one of the points to fall within the iris of the eye. Since the iris is much lighter in color than the pupil, a change in luminance level would occur.

This device superimposes on the camera's video picture of the

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eye a bright dot for each of the four points where the luminance level is checked. This combined video signal is provided as an output signal to drive a monitor. The horizontal and vertical separation of the dots i.e., the four points where the luminance level is checked, can be varied by adjusting the horizontal and vertical separation controls. The fixation monitor is a luminance level adjustment which is set equal to the pupil's luminance level.

To implement the above function, the camera's video output is continuously processed in real time. The horizontal and vertical sychronizing pulses are extracted from the composite video signal. From this we know where the active line begins and ends, and when the first line begins and the last line ends. To do this, the video signal is first buffered, and then is fed into a comparator which acts to clamp sync tip to ground level. The ground referenced video signal is then fed into another comparator and compared against a 200 millivolt reference voltage. The resulting output signal of the comparator is composite sync. This signal is used as a basis for all the horizontal rate signal processing that follows and is also fed into a circuit extracting vertical sync. The output of this vertical sync separator is the basis for all the vertical rate signal processing. The vertical synchronizing pulses are separated from composite sync by using a monostable multivibrator or a "one shot" and a D type flip flop. The composite sync signal is fed into a one shot having a 20 microsecond time constant. Twenty microseconds after low true composite sync fires the one shot, the one shot times out and clocks the flip flop. The flip flop has composite sync on its D input and produces vertical sync as an output. Normally when the

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flip flop is clocked, its D input is high because this would be the active part of the line when H sync would be high. Thus the output of the D flip flop, vertical sync, would remain high. However during vertical retrace when the flip flop is clocked, composite sync is low, and the output of the flip flop, vertical sync, goes low. At the beginning of each line a square wave form is generated. The square waveform begins high at the beginning of the line and drops low at the midpoint of the line, and remains low until the next line. This waveform is then integrated resulting in a triangular waveform with its peak at the midpoint of the line. The voltage level of this signal is then compared against the horizontal separation control voltage. The result is a square waveform low at the beginning of the line, switching high when the triangular waveform level exceeds the control voltage level and remaining high until the triangular waveform voltage level again drops below the voltage level of the horizontal separation control. It then remains low until the end of the line. The "low to high" and "high to low" transition points of this waveform are then extracted, resulting in a narrow pulse for each transition point. These pulses are then ANDED logically with pulses derived in like manner from the vertical rate signal. At the beginning of the vertical interval, i.e., the first horizontal line, a squarewave is generated. This square wave will be high for the first half of the active vertical interval and low for the last half, i.e., the bottom half of the screen. This waveform is then integrated, resulting in a vertical rate triangular waveform with its peak at the midpoint of the active vertical interval. This signal level is then compared to the vertical separation control voltage. This

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produces a square waveform which is low at the beginning of the active vertical interval, switches high when the triangular waveform voltage rises above the vertical separation control voltage, remains high until the triangular waveform voltage again drops below the control voltage. It then remains low until the next vertical interval. Again the "low to high" and "high to low" transitions points are extracted resulting in two pulses. These pulses are then conditioned by horizontal sync to ensure each pulse starts at the beginning of a line and last only for one line. This signal is the output which is ANDED logically with the above derived horizontal rate signal. The combination of these two signals gives us the four points where the luminance is checked. This signal is also combined with the video signal from the camera and is provided as a monitor output signal. This combined monitor picture allows the operator to see where those four points are in relation to the eye. At each of these four points the luminance level of the camera's signal is compared to the preset luminance level of the pupil, which is the voltage level from the "fixation monitor control". If they are equal, the eye is fixated and the patient switch which will be allowed to activate the thermal printer. If they are not equal, the eye is not fixated and the thermal printer will not function if the patient switch is depressed.

The unit operates off standard 120 volts AC, 60 hertz power. Its built in power supply uses a transformer to step this voltage down to 28 volts AC. This voltgage is then rectified using a bridge rectifier which produces both plus and minus 18 volts DC. The AC ripple on both these outputs is filtered by the 1000 UFD

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capacitors. Then the plus 18 volt output is fed into a three terminal linear regulator which produces a highly accurate and pure plus 12 volt output used in supplying power to many of the circuits within the unit. Likewise, the minus 18 volt output is fed into a negative 12 volt three terminal voltage regulator. This output is also used to power the circuits within the device. The output of the plus 12 volt regulator also drives a plus 5 volt regulator whose output is used to power the digital logic circuits in this system.

Physically the unit is housed in a black anodized aluminum enclosure. The front panel contains a power on/off switch, a power indicator light, a horizontal and a vertical cursor position control, and the fixation monitor control. The rear panel provides a BNC connector for both camera video input and monitor video output. Also, there is a connector for the patient hand held switch and a connector for the print head cable. A volume control to adjust the buzzer amplitude, the AC cord and the line fuse are also mounted on the rear panel. An RF output connector is also located on the rear panel. This output is the monitor video signal RF modulated for television channel 2 or 3. This gives the option of using either a video monitor or a TV to view the eye and cursor positions.

VI. Conclusions

In the preceeding pages a two-year research program concerning Multiaperture Optics Technology was described. This effort was heavily slanted towards basic research, meaning to generate a better understanding of the problems encountered with application

of Multiaperture Optics.

In order to remain realistic it was necessary to actually produce three prototypes of MAO devices, which has been done and is described above.

Nevertheless, we consider the most important outcome of this program--the concept to use a fovea (moving or fixed) for image transportation devices. This concept makes it possible to obtain a wide field of view survey of the scenery and at the same time a high resolution image of a small, but important part (e.g., containing the target) of the scenery.

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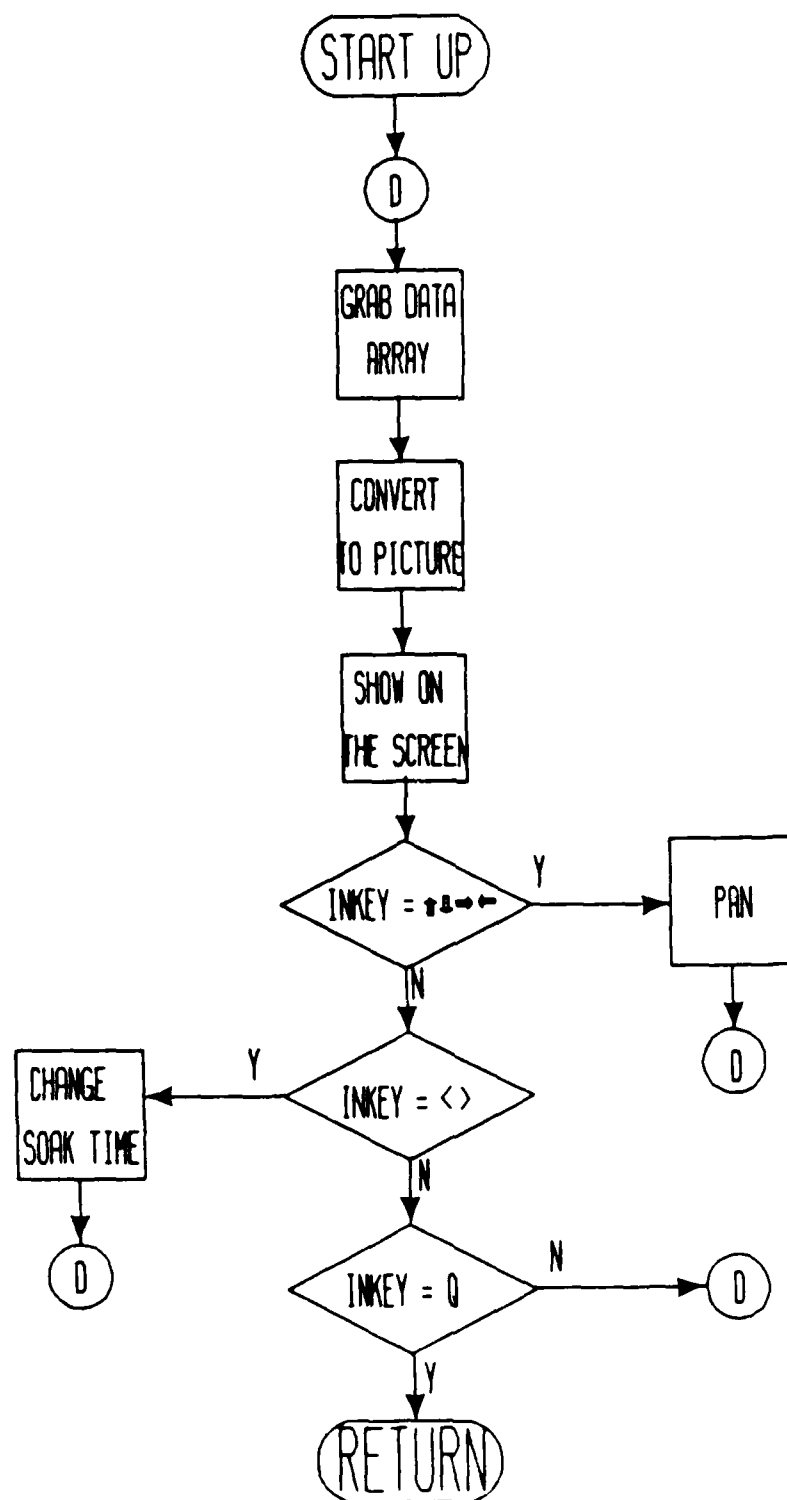
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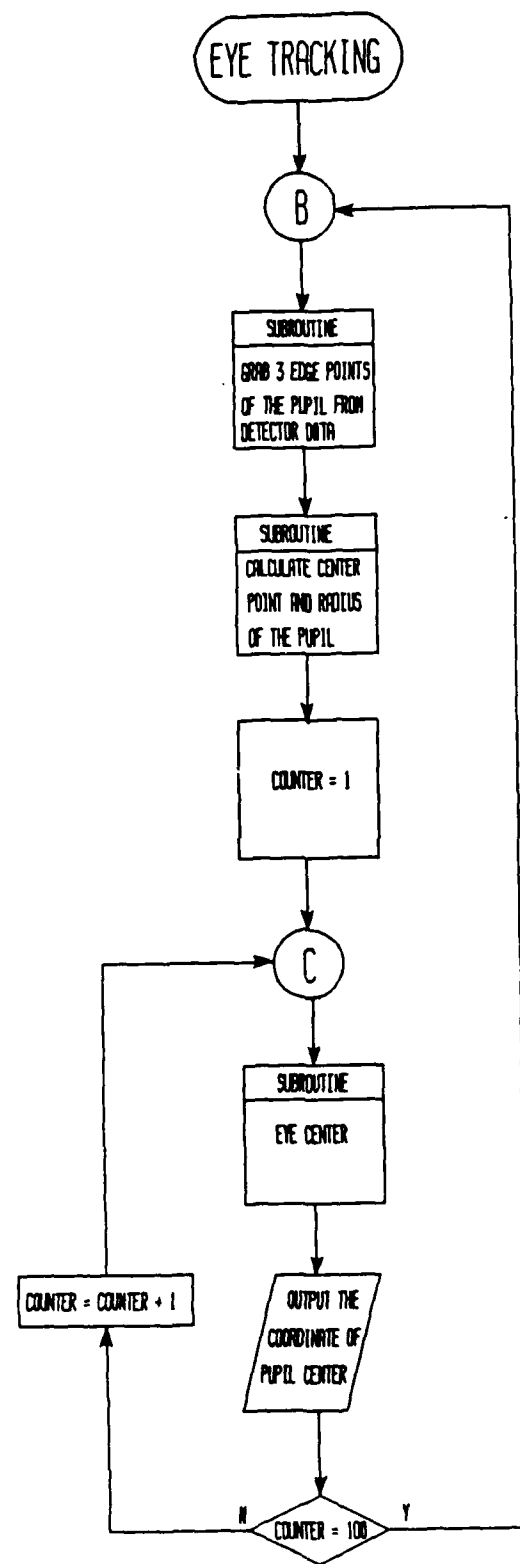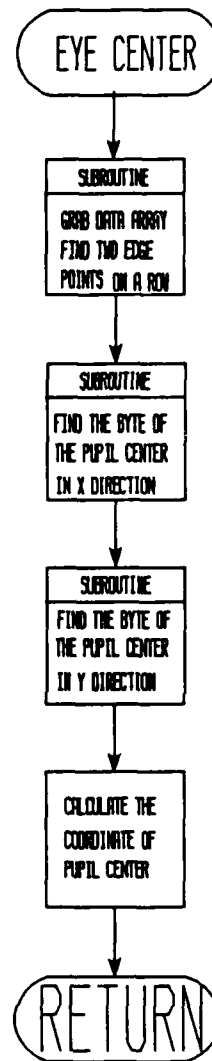
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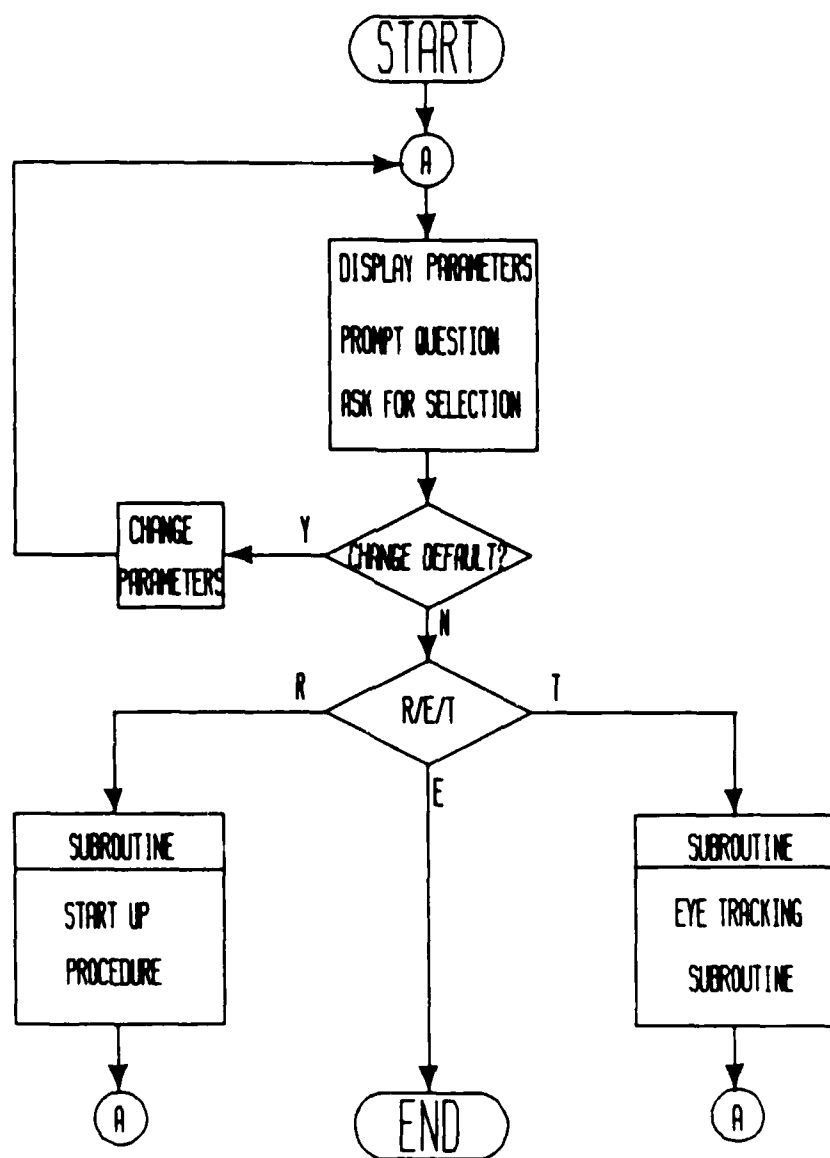
A-1.   Flow Chart of Eye Tracking Program

A-2. Flow Chart of Start Up Subroutine

A-3.   Flow Chart of Tracking Subroutine

A-4. Flow Chart of Eye Center Subroutine

END

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MARCH, 1988

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